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AMERICAN SCIENCE SERIES

A COLLEGE TEXT-BOOK OF GEOLOGY

BY

THOMAS C. CHAMBERLIN

AND

ROLLIN D. SALISBURY

*Heads of the Departments of Geology and Geography
University of Chicago*



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PREFACE

THIS text-book on Geology is intended primarily for college students who are already in possession of the elements of physics, chemistry, and biology. It is intended to serve as a basis for a half-year's work; but by the judicious selection of material to be presented and omitted, the volume may be used for briefer courses, and supplemented by the numerous articles and treatises referred to in the text, it may be made the basis for more extended courses.

In the preparation of the volume it has been the purpose of the authors to present an outline of the salient features of geology, as now developed, encumbered as little as possible by technicalities, and by details whose bearings on the general theme are unimportant. The attempt has been made to make the book readable, in the hope that many persons not in colleges or universities may be interested in following a connected account of the earth's history, and the means by which that history is recorded and read.

The general plan of the work has been determined by the experience of the authors as instructors. Little emphasis is laid on the commonly recognized subdivisions of the science, such as *dynamic geology*, *stratigraphic geology*, *physiographic geology*, etc. The treatment proceeds rather from the point of view that the science is a unit, that its one theme is *the history of the earth*, and that the discussions of dynamic geology, physiographic geology, etc., apart from their historical bearing, lose much of their significance and interest. The effort has been, therefore, to emphasize the historical element, even in the discussion of special themes, such as the work of rivers, the work of snow and ice, and the origin and descent of rocks. This does not mean that phases of geology other than historical have been neglected, but it means that an effort has been made to give a historical cast to all phases of the subject, so far as practicable.

Throughout the work the central purpose has been not only to set forth the present status of knowledge, but to present it so that the student will be introduced to the methods and spirit of the science. To this end the working methods of the geologist have been implied as frequently as practicable. To this end also there has been frankness of statement relative to the limitation of knowledge and the uncertainty of many tentative conclusions.

The theoretical and interpretative elements which enter into the general conceptions of geology have been freely used, because they are regarded as an essential part of the evolution of the science, because they often help to clear the complete conceptions, and because they stimulate thought. The aim has been, however, to characterize hypothetical elements as such, and to avoid confusing the interpretations based on hypothesis, with the statements of fact and established doctrines. Especial care has been taken to recognize the uncertain nature of prevalent interpretations when they are dependent on unverified hypotheses, especially if this dependence is likely to be overlooked.

In many cases the topics discussed will be found to be presented in ways differing widely from those which have become familiar. In some cases, fundamentally new conceptions of familiar subjects are involved; in others, topics not usually discussed in text-books are stated with some fullness; and in still others, the emphasis is laid on points which have not commonly been brought into prominence. Whether the authors have been wise in departing to this extent from beaten paths, the users of the volume must decide.

Especial attention is directed to the map work suggested at various points in the text, as on pages 109, 194, 222, 288, 331, 366, 413, 475, 506, 659, 726, 771, and 845. The use of the topographic maps, folios, and other publications of the United States Geological Survey, somewhat as suggested, will be of great service in making the subject real. The reports of the several State Geological Surveys of the states where this book is used, will also be serviceable. It is suggested that instructors who use the maps and folios mentioned in the text will do well to plan for this work before reaching the ends of the chapters where mention is made of this work. The map work should be interwoven with the class-room

work, rather than added at its close. This adjustment must, of course, be left to the individual instructor.

In addition to the map work it is hardly necessary to emphasize the fact that field work is indispensable to the greatest efficiency. Specific directions for field work, however, even if they were needed, are impracticable, since local fields vary so widely.

UNIVERSITY OF CHICAGO,
May 15, 1909.



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GEOLOGY

PART I

THE MATERIALS OF THE EARTH AND PROCESSES WHICH AFFECT THEM

CHAPTER I

PRELIMINARY OUTLINE

➤ *Geology is essentially a history of the earth and its inhabitants.* It treats of rocks and of the agencies and processes which have been involved in their formation, and from the rocks and their structures it attempts to make out the various stages through which the earth and the living things which have dwelt upon it have passed. It is one of the broadest of the sciences, and brings under consideration certain phases of other sciences, particularly astronomy, physics, chemistry, zoölogy, and botany.

➤ **Subdivisions.** So broad a science has many subdivisions. That phase which treats of the outer relations of the earth is *Cosmic* or *Astronomic Geology*; that which treats of the constituent parts of the earth and its material is *Geognosy*, of which the most important branch is *Petrology*, the science of rocks. That phase which deals with the structural arrangement of the rocks is *Geotectonic*, or *Structural Geology*; that which deals with the forces involved in geologic processes is *Dynamic Geology*; that which treats of the face of the earth, or topographic form, is *Physiographic Geology*; that which concerns itself with the fossils that have been preserved in the rocks, and with the faunas and floras that have lived in the past, constitutes *Paleontologic Geology*, or *Paleontology*. The treatment of the succession of events is *Historical Geology*, which is

worked out chiefly from the succession of beds of rock formed in the progress of the ages.

Besides these general subdivisions, there are special applications of geologic knowledge which give rise to other terms. Thus *Economic Geology* is concerned with the industrial applications of geologic knowledge, and *Mining Geology*, which is a sub-section of economic geology, with the application of geologic facts and principles to mining. Other similar subdivisions might be mentioned.

Important **Dominant processes.** Three sets of processes, now in operation on the surface of the earth, have given rise to most of its surface features. These processes have been designated *Diastrophism*, *Vulcanism* (or *Volcanism*), and *Gradation*. *Diastrophism* includes all movements of the outer parts of the lithosphere, whether slow or rapid, gentle or violent, slight or extensive. Many parts of the land, especially along coasts, are known to be sinking slowly relative to the sea-level, while other parts are known to be rising. The fact that sediments originally deposited beneath the sea now exist, in some places, at great elevations, together with the fact that certain areas which were once land are now beneath the sea, proves that similar changes have taken place in the past. Earthquakes are another illustration of diastrophism. *Vulcanism* includes all processes concerned with the movements of lava and other volcanic products, whether extruded at the surface or not. *Vulcanism* and *diastrophism* may be closely associated, for local movements are often associated with volcanic eruptions. *Gradation* includes all those processes which tend to bring the surface of the lithosphere to a common level. Gradational processes belong to two categories — those which level down, *degradation*, and those which level up, *aggradation*. The transportation of material from the land, whether by rain, rivers, glaciers, waves, or winds, is *degradation*, and the deposition of material, whether on the land or in the sea, is *aggradation*. Degradation affects primarily the higher parts of the lithosphere, while aggradation affects primarily the lower.

THE EARTH IN THE SOLAR SYSTEM

→ **The earth as a planet.** Though supremely important to us, the earth is but one of the minor planets which revolve about the

sun. Of the eight planets, four, Jupiter, Saturn, Uranus, and Neptune, are much larger than the earth, while three, Mercury, Venus, and Mars, are smaller. There are a host of asteroids, but all together they do not equal the mass of the smallest planet. The average mass of the planets is more than fifty times that of the earth, and Jupiter, the largest, has more than three hundred times the mass of the earth. The earth's position is in no sense distinguished. It is neither the outer nor the inner, nor even the middle planet. Even in the inner group of four to which it belongs, it is neither the outermost nor the innermost member, though in this group it is the largest. Its average distance from the sun is about 92.9 million miles, and its period of revolution is $365\frac{1}{4}$ days, a period longer than that of any of the inner planets, and shorter than that of any of the outer ones. Its period of rotation is not very different from that of Mars, but is much shorter than that of the larger planets whose periods of rotation are known. The plane of the earth's revolution approximates the planes of revolution of all the other planets. The orbit of the earth, like the orbits of the other planets, is an ellipse, and its eccentricity is about $\frac{1}{60}$. The inclination of the earth's axis, nearly $23\frac{1}{2}^\circ$ ($23^\circ 27'$), is less than that of some planets, and more than that of others.

Its satellite. The earth is peculiar in having one unusually large satellite, which has a mass $\frac{1}{81}$ of its own. The larger planets have several satellites whose combined mass exceeds that of the moon, and perhaps in some few cases the individual satellites may be larger than the moon; but no other is $\frac{1}{81}$ of the size of the planet about which it revolves. There is little doubt that the moon has played an important part in the history of the earth. It is the chief cause of oceanic tides, and the tides are efficient in the wear of the shores of the oceans and in the distribution of marine sediments. Tides have probably been of importance in the earth's history ever since the ocean came into existence.

Dependence on the sun. By far the most important external relation of the earth is its dependence on the sun, of which it is a mere satellite. Its mass is less than $\frac{1}{333000}$ that of the sun, upon which it depends for nearly all its heat and light, and, through these, for nearly all of the activities that have given character to

its history. A little heat and light are derived from other bodies, and an important source of energy is found in the interior of the earth itself; yet all of these are so far subordinate to the great flood of energy which comes from the sun that they are quite inconsequential. The dependence of the earth on the sun has been intimate throughout its past history, and its future is locked up with the destiny of that great luminary. Geology in its broadest phases can therefore scarcely be separated from the study of the sun; but this falls in the province of the astronomer rather than the geologist.

Meteorites. There are a multitude of small bodies passing through space in varying directions and with varying velocities, and occasionally encountering the earth to which they add their substance. Some of these *meteorites* revolve about the sun like minute planets, but some of them come from such directions and with such velocities as to show that they do not belong to the sun's family. Some consist almost wholly of metal, chiefly iron alloyed with a little nickel (*holosiderites*); some consist of metal and rock intimately mixed (*syssiderites* and *sporadosiderites*); and some consist wholly of rock (*asiderites*). It is now thought that the meteorites throw some light, perhaps important light, on the early history of the earth. They are therefore of interest to the geologist. The amount of material added to the earth by their infall is now relatively slight compared with the whole body of the earth; but their contributions in the distant past may perhaps have been greater.

THE GRAND DIVISIONS OF THE EARTH

The constitution of the earth. The materials of the earth fall into three grand divisions: (1) The *atmosphere*, (2) the *hydrosphere* (water sphere), and (3) the *lithosphere* (rock sphere).

1. *The Atmosphere*

Though the study of the atmosphere constitutes the science of meteorology, the atmosphere is a part of the earth, and as a part of the earth, it falls within the province of geology. It is an intimate mixture of (1) all those substances that cannot take a liquid or solid state at the temperatures and pressures which prevail at the earth's

surface, together with (2) such transient vapors as the various substances of the earth throw off. The first class form the permanent gases of the atmosphere, and consist of nitrogen about 79 parts, oxygen about 21 parts, carbon dioxide about .03 part, together with small quantities of argon, and several other rare constituents. Chief among the second class is water vapor, which varies greatly in amount from time to time and from place to place. Here too, belong the gases which issue from volcanoes, and a great variety of volatile organic substances. Dust and other matter suspended in the air are usually regarded as impurities rather than constituents of the atmosphere; but they are of great importance because they affect its temperature and luminosity, and they facilitate the condensation of moisture.

Mass and extent. The total mass of the atmosphere is estimated to be $\frac{1}{120000}$ of the mass of the earth. It exerts a pressure of about fifteen pounds per square inch at the sea-level. Its density decreases upward, but its actual height is not known. There is no direct evidence of its existence above a few hundred miles, but there are theoretical grounds for believing that it extends out very much farther.

Geologic activity. The atmosphere is the most mobile and active of the three great subdivisions of the earth. Its direct and indirect effects on water and rocks are so great that it must be regarded as one of the great agents of change. It acts chemically upon the rock substance of the earth, causing hardening of the rock in some cases, but more often causing disintegration, by means of which rock is reduced to soil-like material, and prepared for removal by winds and waters. When in motion, the atmosphere acts mechanically on the surface of the land, transporting dust and sand. Its greatest function, however, is in furnishing the conditions for water action. Rains, streams, glaciers, and all the various forms of moving water upon land, are dependent in one way or another on the atmosphere. On the ocean, too, wave action is dependent largely on the winds. Streams and waves, which are the most familiar agents of geologic change, are therefore to be credited as much to the atmosphere as to the hydrosphere.

A thermal blanket. The atmosphere is a thermal blanket to the rest of the earth. In its absence the heat of the sun would reach the surface with much greater intensity than now, and it would be radiated back from the surface almost as rapidly as received. During the night, there would be a degree of cold far greater than that now known to any part of the earth. In passing through the atmosphere, certain portions of the radiant energy of the sun are absorbed. Of the remainder which reaches the surface of the earth, a part is transformed into vibrations of lower intensity which are then more effectively retained by the atmosphere. The air thus distributes and equalizes the temperature. The two constituents of the atmosphere which are most efficient in this work are water vapor and carbon dioxide, and the climate of the earth is believed to have been very greatly affected by the varying amounts of these constituents in the atmosphere, as well as by variation in the total mass of the atmosphere.

The function of the atmosphere in sustaining life and promoting all that depends on life is obvious.

2. *The Hydrosphere*

The water which lies upon the surface of the solid earth, is about $\frac{1}{4950}$ part of the earth's mass. Were the solid part of the earth perfectly spheroidal, this amount of water would constitute a universal ocean a little less than two miles deep. Owing to the unevenness of the surface of the lithosphere, the water is chiefly gathered in great basins or troughs, occupying nearly three-fourths (72%) of the earth's surface. These basins are all connected, so that anything which changes the level of the water in one, changes the level in all.

Oceanic dimensions. The surface area of the ocean is estimated at 143,259,300 square miles. The area of the true oceanic basins is only about 133,000,000 square miles, but these basins are somewhat more than full, and the ocean water laps up on the continental shelves to the extent of more than 10,000,000 square miles. If about 600 feet of the upper part of the ocean were removed, the true ocean basins would be just full. Beneath about 20% of the ocean area, the bottom sinks to depths of between 6,000

and 12,000 feet; under about 53% it sinks to depths of between 12,000 and 18,000 feet; and under 4% it ranges from 18,000 feet down to about 30,000.

Besides the ocean, the hydrosphere includes all the water which constitutes the surface streams and lakes, together with that which permeates the pores and fissures of the outer part of the solid earth. The water of the earth becomes a *hydrosphere* only when the ground water is considered. All other waters of the earth are small in amount, compared with the great mass of the ocean.

Geologic activity. Of all geological agents, water is the most obvious and apparently the greatest, though its efficiency is affected by many conditions, especially the relief of the land, and temperature. Through the agency of rainfall, surface streams, underground waters, and waves, the hydrosphere is constantly modifying the surface of the lithosphere, and at the same time carrying sediment from the land and depositing it in the various basins. The hydrosphere thereby becomes the great agency for the degradation of the land and the building up of the basin bottoms. It is therefore both destructive and constructive in its action. The beds of sediment which it lays down follow one another in orderly succession, each later one lying above an earlier. In this way, they form a time record. And as relics of the life of each age become more or less embedded in the sediments, they furnish the means of following the history of life from age to age. The historical record of geology is therefore very largely dependent upon the fact that the waters have buried in systematic order, relics of the life of successive ages.

The special processes of the hydrosphere will be the subject of discussion hereafter. Suffice it here to recognize its great function in the constant degradation of the land, and in the deposition of the derived material in orderly succession in the basins.

3. *The Lithosphere*

The atmosphere and hydrosphere are envelopes or shells, rather than true spheres, though both penetrate the lithosphere to some extent. The lithosphere, on the other hand, is an oblate spheroid with a polar diameter of 7,899.7 miles, and an equatorial diameter

of about 26.8 miles more. Its equatorial circumference is 24,902 miles, its meridional circumference 24,860 miles, and its surface area about 196,940,700 square miles. Its average specific gravity is about 5.57. The oblateness of the spheroid is the result of the rotation of the earth. Computations seem to indicate that the equatorial bulge is very nearly what it would be if the earth were in a liquid condition. From this the inference has been drawn that the earth was in that condition when it assumed its present form. It is thought by others, however, that the plasticity of the earth is such that it would assume this form under the influence of rotation at the present rate, even if the interior is solid.

Irregularities. It is only in a general view, however, that there is a close approximation to a perfect spheroidal surface. In detail there are very notable variations from it. The equatorial diameters are not exactly equal, and the continental protuberances are, on the average, some three miles above the bottoms of the oceans. The *continental platforms* and *ocean basins* do not correspond accurately with the present land and water surfaces, for about the continental land there are submerged borders, the continental shelves, beyond which the surface of the lithosphere descends rapidly to the depths of the ocean. The continental shelf belongs properly to the continent, but its outer edge is covered by 100 fathoms or less of water. If the upper 600 feet of the ocean were removed, the outlines of the land would correspond quite closely with the border of the true continental platforms. The agencies which produced the continental platforms and abysmal basins, and the great undulations, foldings, and volcanic extrusions of both, are yet subjects of debate.

It is customary to look upon the protrusions of the continents as the great features of the earth's surface, but in reality the oceanic depressions are the master feature. Both in breadth and depth they much exceed the continental protrusions, and if the earth be regarded as a shrunken body, the settling of the ocean bottoms has doubtless been the greatest diastropic movement.

The following tables show the relative areas of the lithosphere above, below, and between certain levels.¹

¹ Article on The Earth, in Johnson's Encyclopædia (Gilbert); also Smiths. An. Rept., 1899, p. 312 (Murray); and Scot. Geog. Mag., Vol. XV, 1899, p. 511.

	Per cent of Surface above	Per cent of Surface below
Contour 24,000 feet above sea-level.....	0.004	99.996
“ 18,000 “ “ “	0.09	99.91
“ 12,000 “ “ “	0.7	99.3
“ 6,000 “ “ “	2.3	97.7
Sea-level.....	27.7	72.3
Contour 6,000 feet below sea-level.....	42.5	57.5
“ 12,000 “ “ “	57.3	42.7
“ 18,000 “ “ “	96.8	3.2
“ 24,000 “ “ “	99.93	0.07

	Per cent
More than 6,000 feet above sea-level.....	2.3
Between sea-level and 6,000 feet above.....	25.5
Between sea-level and 6,000 feet below.....	14.8
Between 6,000 and 12,000 feet below sea-level.....	14.8
Between 12,000 and 18,000 feet below sea-level.....	39.4
Between 18,000 feet and 24,000 feet.....	3.1

From these estimates it appears that if the surface were graded to a common level by cutting away the continental platforms and dumping the matter in the ocean basins, the average plane would lie somewhere near 9,000 feet below sea-level. The continental platform may be conceived as rising from this common plane rather than from the sea-level.

Epicontinental seas. Those shallow portions of the sea which lie upon the continental shelf, or extend into the interior of the continent, such as the Baltic Sea and Hudson Bay, may be called *epicontinental seas*, for they really lie *upon* the lower border of the continental platforms. Those detached bodies of water which occupy deep depressions in the surface are to be regarded as true abysmal seas. Such, for example, are the Mediterranean and Caribbean seas and the Gulf of Mexico, whose bottoms are as low as many parts of the true ocean basin itself.

Diversities of surface. The bottoms of the oceanic basins are diversified by broad undulations which range through many thousands of feet, but they have not those irregularities of form that give variety to land surfaces. The ocean bottoms are also diversified by volcanic peaks, many of which rise to the surface and constitute isolated islands. From many of them, the solid surface slopes rapidly down to abysmal depths, so that many of the volcanic

islands constitute peaks whose heights and slopes would seem extraordinary, if the ocean were removed.

The surface of the land is diversified in a similar way by broad undulations and volcanic peaks, and also by narrower wrinklins and foldings of the crust, and all of these irregularities have been carved into varied and picturesque forms by subaërial erosion. In this respect the surface of the land differs radically from the bed of the sea.

The outer part of the lithosphere is often called the *crust* of the earth. No definite lower limit can be assigned to the crust, and the former notion that it is the solid portion overlying a liquid part beneath, is now generally abandoned. The term crust as now used means the outer, cooler portion of the lithosphere. Its thickness is undefined, but it includes a shell several miles thick, at least, and perhaps a few score miles.

The interior. Concerning the great interior of the earth, little is known except by inference. From the weight of the earth,¹ it is inferred that its interior is much more dense than its surface. From its behavior under the attraction of other bodies, it is believed to be at least as rigid as steel, and its interior cannot, therefore, be liquid, in the usual sense of that term. From the phenomena of volcanoes, and from observations on temperature in deep borings, it is inferred that its interior is very hot. Further inferences concerning its character are less simply stated, and will be referred to later.

¹ Its specific gravity as a whole is about 5.57, and the specific gravity of its outer portion is about 2.7.

CHAPTER II

THE MATERIALS OF THE EARTH AND THEIR ARRANGEMENT

The mantle rock. The great body of the lithosphere is probably composed of solid rock, but the solid rock is very generally covered by a layer of loose material consisting of soil, clay, sand, gravel, and broken rock, known collectively as *mantle rock*. The mantle rock of many places consists of the disintegrated products of underlying rock formations. The upper part of such mantle rock is constantly being blown away by wind and washed away by water, but it is being constantly renewed by the decay of the rock below. The mantle rock of some other areas, as the northern part of North America and the northwestern part of Europe, consists chiefly of an irregular sheet of commingled clay, sand, gravel, and boulders, known as *drift*. The drift was deposited by great glaciers, com-



Fig. 1.— Soil and subsoil arising from the decay of limestone resting on the uneven surface of the rock beneath. Southeastern Missouri. (Buckley.)

parable to those which now cover Greenland and Antarctica. In still other places, especially along the flood plains of streams, the mantle rock consists of deposits made by streams. Along the shores of lakes and seas, there are beach gravels and sands. The thickness of the mantle rock varies from a few inches to hundreds of feet (Fig. 1).

The solid rock. Mantle rock is absent in some places, and there the surface of solid rock appears. It is common on the slopes of steep-sided valleys and mountains, and on the slopes of cliffs which face seas or lakes, and is frequently seen in the channels of swift streams, especially where there are falls or rapids. In all lands inhabited by civilized peoples, there are numerous wells and other excavations ranging from a few feet to several hundred feet in depth, and occasional wells and mine-shafts go much deeper. Even in the shallower excavations solid rock is often encountered, and in most regions excavations as much as two or three hundred feet deep reach it. It may, therefore, be accepted as a fact that the upper surface of the solid rock is nowhere far below the surface.

Varieties of solid rock. If the mantle rock were stripped from the land, the rock beneath would be found to be made up of many kinds of rocks, all of which may be grouped into three great classes. By far the larger part of the land surface would be of rock arranged in layers (*stratified* rock), and the remainder would be of rock which is without distinct stratification. The rocks without distinct stratification are divided into two great groups, *igneous* rocks, and *metamorphic* rocks.

The essential feature of *stratified* rock is that it is arranged in layers. The layers may be distinct or indistinct, and they may be thick or thin. Thick layers are often made up of many thinner ones. Fig. 2 shows rock which is distinctly stratified.

In composition, much stratified rock corresponds somewhat closely with the sediments now being carried from the land and deposited in the sea; that is, these rocks are made up of pebbles, sand grains, or particles of mud, cemented together. The bedded arrangement of stratified rocks and of recent sediments is the same, and the markings on the surfaces of the layers, such as ripple-marks, rill-marks, wave-marks, etc., are identical. Furthermore,

the stratified rocks of the land, like the recent sediments of the sea, frequently contain the shells and skeletons of animals, and sometimes the impressions of plants. Most of the relics of life found in the stratified rocks belonged to animals or plants which lived



Fig. 2.—Stratified rock. Trenton Limestone, Fort Snelling, Minn. (Calvin.)

in salt water. Because of their structure, their composition, their distinctive markings, and the remains of life which they contain, it is confidently inferred that most of the stratified rocks which lie beneath the mantle rock of the land were originally laid down

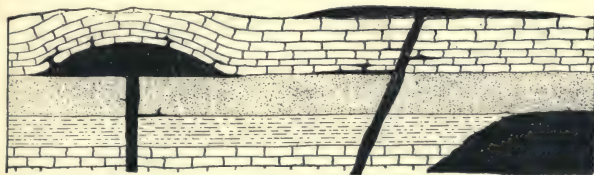


Fig. 3.—Diagrammatic representation of the relations of igneous rock to stratified rock. The igneous rocks, represented in black, have been forced up from beneath.

in beds beneath the sea, and that the familiar processes of the present time furnish the key to their origin.

Igneous rocks may be loosely defined as hardened lavas. They sustain various relations to the stratified rocks, as illustrated by

Fig. 3, where some of the igneous rock, indicated by black, is represented as lying beneath the stratified rock, and some above it, while some is interbedded with the stratified rock, and some cuts across its layers. From these relations it is possible to tell something of the order in which the rocks were formed. Where the stratified rocks are broken through by lavas, it is clear that the stratified rocks were formed first, and the lavas intruded later.



Fig. 4.— Metamorphic rock. (Ells. Can. Geol. Surv.)

Lava sheets intruded between beds of stratified rock can be told from those which flowed out on the surface and were subsequently buried, for in the former case the sedimentary rocks, both above and below the igneous rock, were affected by the heat of the lava, while in the latter case only those below were so affected.

Most *metamorphic rock* has cleavage, that is, a tendency to break in one direction rather than in another. The cleavage of metamorphic rock may look much like stratification, but it is really very different. The tendency to break along certain planes is not due to the fact that the rock was deposited in layers originally, as in the case of stratified rock, but is the result of the changes which

the rock has undergone since it was formed. The structure shown in Fig. 4 is known as *schistosity* — a structure characteristic of metamorphic rock. The planes of cleavage, often irregular, are independent of the original planes of stratification in those cases where the rock was originally stratified. Metamorphic rock may be derived from igneous rock, as well as from sedimentary.

More commonly than otherwise, metamorphic rocks lie beneath sedimentary beds, or come to the surface from beneath them, and they are often broken through by igneous rocks.

Igneous Rocks

How they come to be at the surface. Some of the igneous rocks which appear at the surface and beneath the mantle rock, have been extruded from volcanoes. From some volcanoes, such as those of Hawaii, lava flows in streams, and as it cools, hardens into solid rock. From others, such as Vesuvius, fragments of hot rock are hurled high into the air and fall about the vents. Fragmental material ejected from volcanoes forms *pyroclastic* (fire-fragmented) rock. Pyroclastic rock is, in many cases, lava blown into small pieces which harden separately.

Lava sometimes flows out on the surface through long fissures, which extend down to great depths. Such extrusions of lava are called *fissure eruptions*. There have been few great fissure eruptions in historic time, but in recent geologic time, there were great eruptions of this sort in the northwestern part of the United States, as well as in some other parts of the earth. All rock matter extruded from volcanoes and fissures is *extrusive rock*.

Besides being thrown out or poured out from volcanoes and fissures, igneous rocks appear at the surface in other ways. Much lava which rises from the deep interior does not reach the surface, but is *intruded* into rock which lies above the source from which it started. If intruded lava fills cracks in the earth, it forms *dikes*. If it forces itself in between layers of rock, it may take the form of *intruded sheets*, or *sills*. If it accumulates below the surface in masses, arching up the overlying beds of rock, it forms *laccoliths* (Fig. 5). If it breaks and lifts its cover, instead of arching it up, the lava is called a *bysmalith*. Laccoliths and bysmaliths may

be large enough to form good-sized mountains. The Henry Mountains of Utah are laccoliths. Very great intrusions of rock of massive form are sometimes called *batholiths*. Rock solidified from lava well below the surface is called *plutonic rock*.

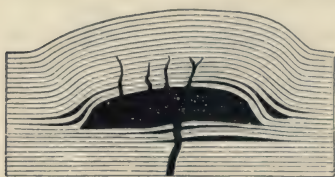


Fig. 5.— Ideal cross-section of a laccolith with accompanying sheet and dikes. (Gilbert, U. S. Geol. Surv.)

Sills, laccoliths, bysmaliths, batholiths, etc., are formed beneath the surface; but if the covering rock is worn away, as it may be by erosion, the igneous rock appears at the surface. Much of the igneous rock

which is now at the surface or concealed by the mantle rock only, is intrusive rock, laid bare by the removal of its original cover.

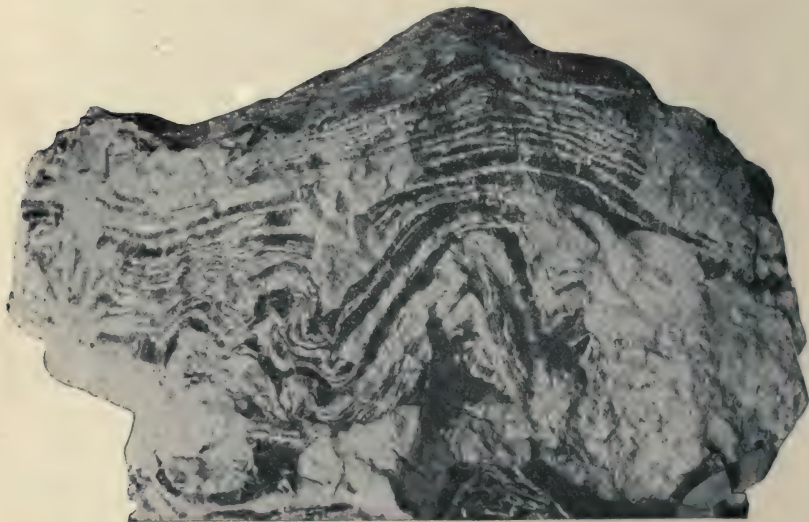


Fig. 6.— Flow structure in volcanic glass. About half natural size. (Photo. by Church.)

The larger structural features of igneous rock. Igneous rocks have certain structural features which distinguish them from other rocks. Thus laccoliths, bysmaliths, and batholiths are *massive*.

This term means not simply that the rock occurs in large bodies, but that the rock has no distinct *cleavage*. It is not in beds, and it is not schistose. Sills and extrusive flows of lava often take on the form of *sheets*. When one extrusive sheet of lava overlies another, the succession of sheets has some resemblance to stratified rock; but the materials of the several sheets show little indication of arrangement in layers. The material of the sheets, however, sometimes has a peculiar structure developed by the flow of the

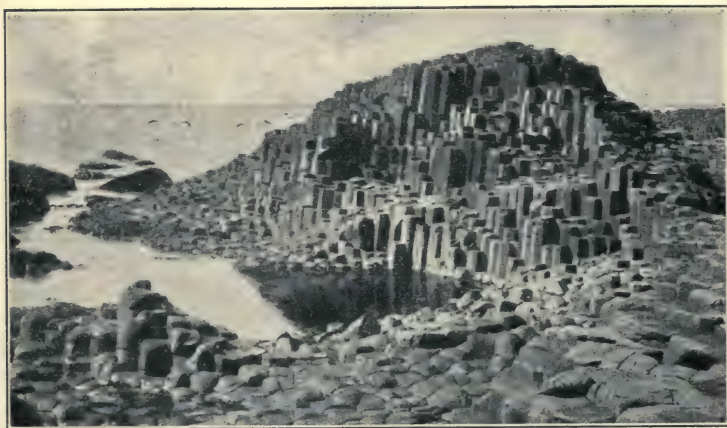


Fig. 7.— Columnar structure in igneous rock. Giants' Causeway.

lava after it had become stiff from cooling. This structure is known as *flow structure* (Fig. 6). In some places, the lava, on cooling, develops a *columnar structure* (Fig. 7) which appears to be the result of contraction as the lava cools. The columns are generally perpendicular to the surface of cooling.

The explanation of the columns is probably somewhat as follows: The surface of the lava contracts about equally in all directions on cooling. The contractile force may be thought of as centering about equidistant points. About a given point, the least number of cracks which will relieve the tension in all directions is three (A, Fig. 8). If these radiate symmetrically from a point, the angle between any two is 120° , the angle of the hex-

agonal prism. Similar radiating cracks from other centers complete the columns (*B*, Fig. 8). A five-sided column would arise from the failure of the cracks to develop about some one of the

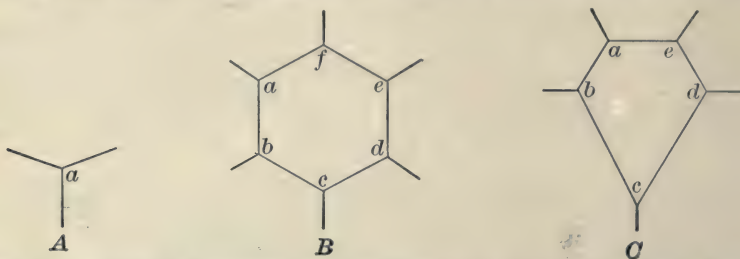


Fig. 8.— Diagrams to illustrate the formation of columns of basalt: *A*, the first stage in the development of a hexagonal column. *B*, the completion of a hexagonal column. *C*, a pentagonal column.

points (*C*, Fig. 8). All igneous rocks are likely to be affected by cracks or *joints*, which run through them in various directions, but joints are not peculiar to igneous rocks.

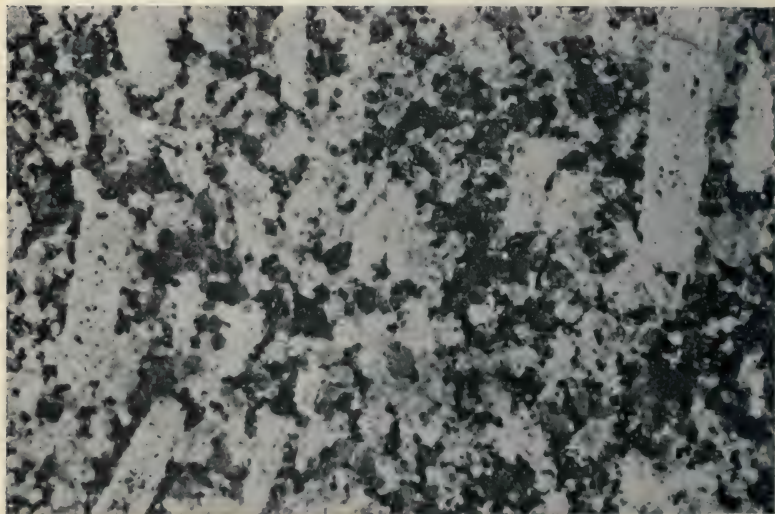


Fig. 9.— Granitic rock, about half natural size. The white patches represent crystals of one or two kinds of mineral, and the dark parts represent crystals of others.

Pyroclastic rocks have somewhat the structure of sedimentary rocks. If the fragmental volcanic matter accumulates on the surface of the land, it often lacks distinct stratification; but if it falls or is washed into water, it may be assorted and stratified. In this case it is distinguished from elastic rock by its constitution.

Minor structural and textural features of igneous rock. Most *igneous rocks* are made up of *interlocking crystals* of different sorts. These crystals may be so small that they are not readily distinguished by the eye, or they may be so large as to be easily seen, or

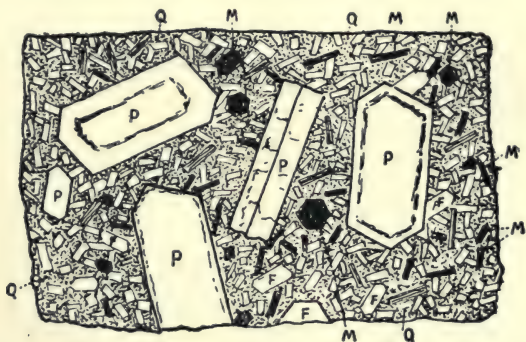


Fig. 10 —Porphyritic structure. *P*=phenocrysts of feldspar. The smaller crystals are of feldspar, mica, and quartz. (Watts.)

some may be large and some small. If they are large enough to be distinct to the eye even without close scrutiny, the rock is coarsely crystalline. It is proposed to call all such rocks *phanerites*. In the case of phanerites, the interlocking of the crystals is evident (Fig. 9). If the crystals are so small as not to be readily seen except by the help of a magnifying glass, the rock is an *aphanite*. In all igneous rocks, the crystals are of somewhat unequal size; but in some, there are certain crystals, usually of some one mineral, which are much larger than the others — so much larger as to be conspicuous. The rock is then said to be *porphyritic* (Fig. 10). The smaller crystals in which the larger ones are set may be so small as not to be readily distinguished (aphanitic), or they may be separately visible (phaneritic).

Some igneous rock looks like dark colored glass. Such rocks are indeed glass, and, like manufactured glass, were solidified from a liquid. Volcanic glass (obsidian) is one phase of solidified lava. It is formed when the liquid lava solidifies quickly, before the crystals have time to grow. Some igneous rock is made up partly of glass and partly of crystals, and between the rock which is all glass and that which is all crystals there are all gradations. Whether the lava becomes glassy or crystalline on hardening, or whether it



Fig. 11.— Scoriaceous texture. About $\frac{1}{2}$ natural size. (Photo. by Church.)

is partly the one and partly the other, depends on the conditions under which it solidifies. All liquid lava contains the materials out of which crystals may be formed, under proper conditions.

Glassy and partly glassy rock may be compact or porous. Porous rock of the type shown in Fig. 11 is called *scoriaceous*. Rock of this sort is really lava froth, solidified, and the pores are the spaces occupied by gases when the lava hardened. The bubbles were sometimes large and sometimes small. *Pumice* is porous volcanic glass, the pores being small.

Besides these varieties of texture which originate as lava hardens, there are the textures peculiar to *pyroclastic rocks*. When quanti-

ties of *volcanic dust*, etc., (sometimes called *volcanic ash*) become coherent, as by cementation, the resulting rock is called *tuff* (or *volcanic tufa*). If the constituents are largely coarse, instead of fine, the resulting rock is *volcanic agglomerate*. Pyroclastic rocks are less abundant than other volcanic rocks.

The nature of lava. We commonly think of lava as melted rock, but this view is hardly the correct one. Lava is rather a solution of mineral matter in mineral matter. A simple analogy may illustrate what is meant. If pounded ice and salt are mixed together at a temperature of 30° F., the two form a liquid, though the temperature is too low to melt either one. We commonly say the salt is dissolved, but it would be just as correct to say that the ice is dissolved. The ice did not melt, because the temperature was too low to melt it. The two minerals, ice and salt, are dissolved in each other, and the solution takes place at a temperature below the melting point of either. Something of the same sort appears to take place when rock becomes liquid. The liquid form is probably assumed at a temperature below that which would be necessary to melt the minerals which make up the lava.

The propriety of regarding lava as a solution of minerals in minerals is shown in another way. Granite, an igneous rock, is made up chiefly of three minerals, *quartz*, *feldspar*, and *mica*. These minerals melt at different temperatures. If lava were nothing more than mineral matter melted, the several minerals should solidify from the liquid as it cools *in the reverse order of their fusibility*. Of the above minerals, quartz would be the last to melt, and if lava were merely melted rock, quartz should be the first to take the solid form as the lava cools, and it should become solid when the lava reaches the fusing temperature of this mineral. But this is not what happens. The least fusible mineral may be the last to take the solid form. In other words, *the order in which the various minerals solidify from the liquid lava is independent of their fusibility*. This would not be the case if they were simply melted.

The liquid lava is essentially a fluid glass. It is analogous to common glass, which is a silicate of potash, soda, or other base, except that manufactured glass is relatively free from iron and other coloring substances which abound in the lavas, rendering them

dark and more or less opaque. Lavas, too, are usually mixtures of several silicates, while manufactured glasses consist of only one, or at most a few. Furnace slag is essentially an artificial lava.

Solidification and crystallization. When a lava is cooled quickly, the commingled silicates solidify in their diffused condition essentially as they were in the liquid; for there is no time for the molecules of one kind to come together in regular systematic order, as is necessary to form crystals. The essential feature of crystallization is this systematic arrangement of the molecules of a given kind, according to a definite plan, giving a specific crystal form.

In a thick viscid liquid, this systematic arrangement of molecules into definite crystal forms takes place slowly, for the crystalline force in the silicates is far less energetic than that in water, which crystallizes into ice rapidly and with great force. Because of the slowness of crystallization, the solidification of the lava may catch the process of crystallization at any stage. If the lava is cooled quickly, the result is a glass; if less quickly, part glass and part crystals; if slowly enough, all becomes crystalline. In general, *the slower the growth, the larger the crystals.*

The crystal forms of the different minerals are unlike. Thus a crystal of quartz always takes the form of a six-sided pyramid (Fig. 51), if nothing interferes with its growth. The crystals of feldspar, mica, etc., take other forms (Figs. 49 and 50). All crystal forms are grouped into six (sometimes made seven) fundamental systems of crystallization, and there are a multitude of variations of special form in each. The treatment of these forms belongs to mineralogy.

The first crystals to form from a liquid lava tend to assume perfect forms, but when many crystals are forming at the same time, as is generally the case when lava solidifies, the crystals interfere with one another's growth. The result is that they interlock in all sorts of ways, and the forms of most of the crystals are very imperfect.

Successive stages of crystallization. Since eruptions take place intermittently, it is obvious that cooling of the lava may be in progress beneath the surface during the intervals between eruptions. After a certain stage of partial crystallization has been reached

during such time of quiet, a renewal of eruption may take place, and the whole mass of lava may be shifted into new surroundings, and a second phase of solidification may be superposed on the one already started. The rock may then show two phases of crystallization: (1) Large crystals of the kind or kinds which developed in the lava during the first stage of slow subterranean cooling; and (2) small crystals or glass developed during the more rapid cooling under the new conditions. The result is large crystals set in a matrix of small crystals or of glass. Rock of this physical composition is *porphyry*, a term which has a textural but not a mineralogical significance.

Composition of Igneous Rocks

Nearly all the chemical elements known on the earth are found in igneous rocks, though but few of them are abundant. These few are regarded as the normal or essential constituents, while the rarer substances are regarded as incidental. The relative amounts of the more abundant elements in the crust of the earth, as nearly as now known, are shown in the following table:¹

Element	Symbol	Per cent in the Solid Crust
Oxygen	(O)	47.02
Silicon	(Si)	28.06
Aluminum	(Al)	8.16
Iron	(Fe)	4.64
Calcium	(Ca)	3.50
Magnesium	(Mg)	2.62
Sodium	(Na)	2.63
Potassium	(K)	2.32
Titanium	(Ti)	.41
Hydrogen	(H)	.17
Carbon	(C)	.12
Phosphorus	(P)	.09
Manganese	(Mn)	.07
Sulphur	(S)	.07

It will be seen that only eight of the elements exceed one per cent, and no other one reaches one-half of one per cent. Many of the elements that are of the utmost importance in the affairs of men occur in quantities too small to be estimated in percentages. The precious metals, and even some of the more common ones,

¹ Clarke, F. W. Bull. 168, U. S. Geol. Surv.

as lead, zinc, and copper, are of little importance *quantitatively*. We do not know just how the various elements of igneous rock are united in the liquid lava, but their combinations after the lava has become solid may be determined.

Union of elements. In a general study of the igneous rocks we may for the present neglect all but the first eight of the elements. Out of these elements come various chemical combinations when the lava solidifies; out of the combinations come the various minerals; and from the combinations of the minerals come various kinds of rocks. The union of oxygen with the other seven elements may be taken as a fundamental step in this series of combinations. The result is the following oxides: Silica (SiO_2), alumina (Al_2O_3), the ferrous, ferric, and magnetic oxides (FeO , Fe_2O_3 , and Fe_3O_4), magnesia (MgO), calcium oxide (lime) (CaO), soda (Na_2O), and potash (K_2O). The oxygen sometimes unites in proportions different from those here given, but exceptions may be neglected here.

Of these nine oxides, silica acts as an acid, or more strictly as an acid anhydride. All the rest, except the magnetic oxide of iron, and sometimes the oxide of aluminum, act as basic oxides. The proportion of silica in igneous rocks is so significant that all such rocks are sometimes divided into three groups, as follows: Those with more than 65% of silica are *acidic*; those containing 55 to 65%, *intermediate*; and those containing less than 55% *basic*.

The union of silica (SiO_2) and lime (CaO) forms calcium silicate, CaO, SiO_2 , or CaSiO_3 . The union of silica and magnesia forms magnesium silicate, MgO, SiO_2 , or MgSiO_3 . Corresponding unions of silica and the other oxides named, give rise to other silicates.

Formation of minerals. Since but one of the leading oxides (silica) that abound in the average lava plays the part of an acid, a very simple conception of the general nature of igneous rocks may be reached by noting that they are mostly silicates of the seven leading basic oxides; that is, the oxides of alumina, potash, soda, lime, magnesia, and iron. This general idea is a very useful one, and represents a most important truth; but in its use we must not forget that there are many exceptions. Sulphur, phosphorus, chlorine, and other elements unite with the bases to form sulphates, sulphides, phosphates, phosphides, chlorides, etc. So also there

are many minor bases that form silicates; and these minor bases unite with the minor acids to form many more or less rare minerals. Again, there are native metals in some igneous rocks. But altogether these minor compounds hardly reach more than one or two per cent of the whole.

There are, however, two exceptions of more importance. In the liquid lava the acid and basic elements are not always evenly matched. When there is an *excess of silica*, a portion remains free and takes the form of *quartz* (SiO_2). If there is an *excess of the basic oxides*, the weakest one is usually left out of the combination. This is commonly the *iron oxide*, which then usually takes the form of *magnetite* (Fe_3O_4). It is a singular fact that quartz often forms when there is no excess of silica, and magnetite when there is no excess of base. Quartz (free acid anhydride) and magnetite (free basic oxide) sometimes occur in the same rock. The explanation of this is yet to be found. The oxides of silicon and iron form rather important exceptions to the general statement that igneous rocks are made up mostly of silicates, but, thus qualified, the statement expresses the essential truth.

Sources of complexity. But here simplicity ends, and the sources of complexity are several. In the first place, silica unites with the bases in different ratios, and thus gives rise to *uni-silicates* or *ortho-silicates* (ratio of oxygen of base to oxygen of silica, 1:1), *sub-silicates* (the above ratio more than 1), *bisilicates* (ratio 1:2), *tri-silicates* or *poly-silicates* (ratio 1:3 or higher), etc. All the bases are not known to combine in all these ways, but many do in more than one.

If the silica united with each of the bases by itself alone, the results would still remain comparatively simple; but instead, it sometimes unites with two or more at the same time. Thus we may have an aluminum-calcium silicate. Not only this, but the different silicates may crystallize together in the same mineral. Thus a crystal may be made up of alternating layers of different silicates. As such alternations are not governed by any known mathematical law, there is no determinate limit to the number of combinations that may arise.

As a result of all this fertility of combination, the total number

of silicious minerals in igneous rocks is large. Geology deals with these minerals as constituents of the earth, but only a few of them are so abundant as to require special notice here. It may be remarked also that, as they occur in the rocks, only a few of them can be identified by simple inspection, partly because some of them look much alike, and partly because the crystals are often minute and intricately intermixed.

Minerals of igneous rocks. Fortunately for the simplicity of geological study, a few minerals make up the great mass of the igneous rocks. These few are *quartz*, the *feldspathic minerals*, the *ferro-magnesian minerals*, and the *iron oxides*.

Quartz is the free acid already mentioned. Some of its leading characteristics are given on p. 80. Crystals of quartz are six-sided prisms, normally, capped by six-sided pyramids (Fig. 51); but in igneous rocks their forms are usually very imperfect.

The *feldspathic group* of minerals embraces those formed by silica in union with alumina, together with either potash, soda, or lime, or two or more of these together. The feldspathic minerals are normally light in color, ranging from white to red, gray, or greenish. The feldspars are minerals of the first importance in igneous rocks. The varieties of feldspar are given on p. 77.

The *ferro-magnesian group* embraces minerals formed by the union of silica with iron, magnesia, and lime, together with more or less of the other basic oxides. The ferro-magnesian minerals are normally dark (commonly greenish) from the presence of iron, the great coloring element of rocks; but the color distinctions do not hold good in detail, and cannot be safely trusted as a means of identification.

Among the *ferro-magnesian minerals* the most important are the *pyroxenes* (p. 80), the *amphiboles* (p. 75), and the *micas* (p. 79). The pyroxenes and amphiboles have nearly the same chemical composition, but differ in crystal form and physical properties. *Hornblende* (an amphibole) has been melted, and on cooling under proper conditions found to take on the form of *augite* (a pyroxene). *Pyroxene* is sometimes altered into *uralite*, one of the amphiboles. The pyroxenes and amphiboles are among the most abundant of the dark minerals in crystalline rocks.

The two leading *micas* are the iron-magnesia mica, *biotite*, or black mica, and the potash mica, *muscovite*, or white mica, the familiar "isinglass" of the stove-door. Chemically, muscovite should go with the potash feldspars, but it is distinguished from them by its crystalline habit and physical properties. Chemically, too, biotite should go with the pyroxenes and amphiboles, which it closely resembles except in the form and properties of its crystals.

Two *iron oxides*, magnetite (Fe_3O_4) and hematite (Fe_2O_3), are widely disseminated in igneous rocks, but they are far less abundant than the silicates. They constitute the free bases already mentioned.

Summary of salient facts. The salient facts are, therefore, (1) that out of the 70-odd chemical elements in the earth, eight form the chief part of it; (2) that one of these elements uniting with the rest forms nine leading oxides; (3) that one of these oxides acts as an acid and the rest as bases; (4) that by their combination they form a series of silicates of which a few are easily chief; (5) that these silicates crystallize into a multitude of minerals of which again a few are chief; and (6) that these minerals are aggregated in various ways to form rocks. Possessed of these leading ideas, we are prepared to turn to the consideration of some of the conditions under which these combinations take place in the formation of rocks from liquid magmas.

Classification of Igneous Rocks

Several features are involved in the current classification of igneous rocks. Some of these features have been noted already, but they may be recapitulated here. All fragmental igneous rocks are *pyroclastic*, and pyroclastic rocks may be tuffs, agglomerates, etc. (p. 21). Rock formed by the solidification of lava without the development of crystals, is *obsidian*, if not porous. If porous (hardened rock-froth), they are pumice, scoriaceous glass, etc. If the rock is largely glass, but partly of small crystals, it is sometimes called *pitchstone*, because its freshly fractured surface looks like pitch or resin. When scoriaceous rock has its cavities filled by minerals deposited from solution, the rock becomes an *amygdaloid*. *Porphyry* has already been defined (p. 23). All these names are based on texture, rather than on mineralogical or chemical composition.

Most igneous rocks are wholly crystalline, and are classified on the basis

of their composition. Their chemical composition determines their mineral composition, and the naming of the rocks is based on the minerals they contain. It will be seen, however, that the chemical composition is the more fundamental. The number of varieties of igneous rock is very large, but only a few of the more important need be mentioned here.

The granites. This name was originally used to designate a granular, i. e., a distinctly crystalline, rock, and it is still popularly and properly so used. In scientific treatises it has usually been confined to a rock composed



Fig. 12.—Graphic granitic (or pegmatitic) texture. Nearly natural size. (Photo. by Church.)

chiefly of crystals of quartz, feldspar (especially orthoclase, (p. 79), and mica. It has recently been proposed to give it again a more general application, though not quite its original one, by including under it all phanerites (p. 59) composed chiefly of quartz and feldspar of any kind, with mica, hornblende, or other minerals in subordinate amount. In normal granite, the crystals are distinct and sometimes large (Fig. 9). They are intimately mingled with one another, and in growing, interfered more or less with each other and so became interlocked. The granites are among the most common and easily recognized of the phanerites. Their color is determined largely

by the feldspar, the red and pink varieties of the mineral giving rise to red granite, and the whitish varieties to gray granite.

Granites vary widely from their type form by the addition and substitution of other minerals, and these sometimes become as prominent as the type minerals. Thus other feldspars sometimes take the place of the orthoclase (p. 79), or accompany it; hornblende and other minerals take the place of the biotite, or occur with it, and so on. Whenever one of these replacing or accessory minerals is abundant, its name is often prefixed, as hornblende-granite. Granite grades almost insensibly into other types of igneous rock, as syenite, diorite, etc. Variations also arise from the absence of one of the three leading minerals.

The granites were formed from a lava rich in silica (68–70%), alumina, potash, and soda, but generally poor in lime, iron, and magnesia. Incidentally other substances are present. Granite is generally an intrusive massive rock which solidified slowly under conditions which permitted complete crystallization, with the development of large crystals.

When rock of the composition of granite is banded, it is *gneiss* (p. 84). The texture of *graphic granite* (see *pegmatite*, p. 86) is notably peculiar, due to the simultaneous crystallization of the quartz and feldspar (Fig. 12).

The syenites. The term syenite (from Syene on the Nile, where this sort of rock occurs) is now applied to a rock consisting essentially of feldspar and hornblende (with or without mica); but there is a complete gradation from the granites to the syenites. The syenites are richer in iron and magnesium than the granites, and poorer in silica (about 58–60%). The syenites also grade into other classes of rock as do the granites, and are named by similar prefixes, as augite-syenite, etc. The syenites are red or gray, according to the color of the feldspar, and are usually darker than the granites, which they resemble. The texture of syenite is like that of granite.

The diorites. The diorites are rocks which crystallized from lavas having about the same amount of silica as the lavas of the syenites, but poorer in the alkalis, and richer in the earthy bases. In current usage, diorite is defined as a rock composed of an intimate mixture of crystals of hornblende and a plagioclase feldspar. It differs from syenite in having plagioclase feldspar (p. 77) instead of orthoclase. By substitutions and the addition of accessory minerals, the diorites grade toward the granites and syenites on the one hand, and toward the gabbros on the other.

The gabbros. The name gabbro was formerly applied to a coarse-grained basic rock consisting of labradorite (p. 78) and diallage (p. 76); but the name has been extended gradually until it embraces a large group of rocks whose principal minerals are plagioclase (normally labradorite) and pyroxene (normally diallage), with magnetite or ilmenite (titanium iron oxide). The gabbros are usually dark colored and rather heavy. The pearly luster of the cleavage faces of the diallage gives a peculiar sheen to a fresh surface of the rock, in many cases.

The Peridotites. These stand at the basic end of the series, having been formed from a magma in which the silica was low (39–45%), as were also the alumina, lime, and the alkalis, but in which the magnesia was high (35–48%). The rock consists very largely of the mineral *olivine* (a magnesium-iron silicate), associated with pyroxene, magnetite, and other very basic minerals. Little or no feldspar is present. The peridotites are much less abundant than the preceding classes.

Closely allied to the peridotites are rocks which are made up largely of a single basic mineral, as *augite*, *pyroxenite*, *hornblendite*, rocks essentially formed of the minerals augite, pyroxene, and hornblende, respectively.

The basalts. The term basalt is used in a somewhat comprehensive way for dark, compact, igneous rocks that appear to be nearly homogeneous owing to the smallness of the crystals which are usually so minute as to be identifiable only under the microscope. The leading minerals are plagioclase (usually labradorite or anorthite) and pyroxene (usually augite), with olivine and magnetite or ilmenite usually present. There is a considerable range in chemical nature, but the basalts are relatively poor in silica, and usually in potash and soda, but rich in lime, magnesia, and iron. The basalts are classed as basic, and are sometimes highly so. The lavas of basaltic flows were especially fluid, and spread out in thin sheets when poured out upon the surface. In cooling, basalt is prone to take on a columnar structure (p. 17). The columns of Giant's Causeway and Fingal's Cave are familiar examples.

The dolerites. The basalts graduate insensibly into the dolerites; indeed the dolerites may be regarded as basalts of coarser crystallization. The minerals are evident to the eye and range up to medium size. In the growth of the minerals, one crystal frequently encloses others. The dolerites have many varieties, due either to accessory minerals, or to the development of some of the constituents more amply than the others. The type may be said to consist of plagioclase and augite, the other minerals being regarded as accessories. The varieties are usually designated by prefixes, as *olivine-dolerite*, etc., but special names are also used for some varieties.

The ancient dolerites have usually undergone internal changes and such rocks are often called *diabases*. While the use of the term has not been uniform, it accords with the better practice to regard the diabases simply as partially altered dolerites and basalts.

General names. The difficulty of distinguishing many of the foregoing rocks from each other by any means available in the field, owing to the minuteness of the crystals, and to the gradation of one type of rock into another, makes it desirable to employ certain general names which will correctly express the leading character of the rock without implying a knowledge of the precise mineral composition. A convenient term of this kind is *greenstone*, which merely indicates that the ferro-magnesian minerals are prominent, and usually give a greenish or greenish-black cast to the rock. The green-

stones embrace the diorites, dolerites, some of the gabbros, and the basalts, and may even extend to the peridotites and perhaps to others. Another convenient name is *trap*, which may be used for any dark, heavy igneous rock, such as basalt. The term basalt is sometimes used in much the same way.

Varieties of rock dependent upon conditions. From what has preceded, it is clear that the chemical nature of the liquid magma determines the mineralogical composition of the rock, if it is crystalline. But it may now be pointed out that the same lava which made a plutonic granite, might have made a porphyry, an obsidian, a pumice, or a tuff, under other conditions of cooling and hardening. The same is true of other varieties of the phanerites.

The Disruption of Igneous Rocks

At the surface, igneous rocks are subject to mechanical disruption, and to chemical change which results in decay.

Mechanical disruption. The great agent of mechanical disruption is change of temperature. Heating by day and cooling by night produce some such change in rock as that effected by the sudden heating of cold glass or the sudden cooling of hot glass.

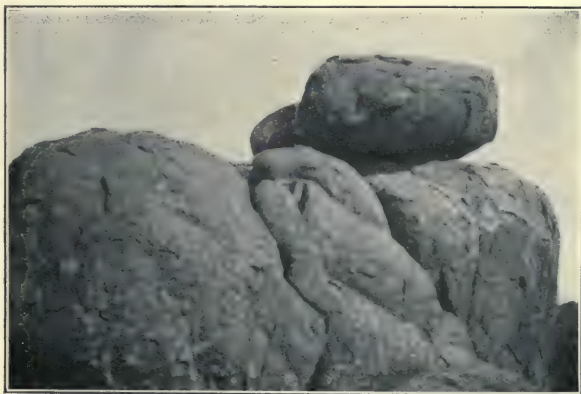


Fig. 13.—Exfoliation of granite. Wichita Mountains, Okla.

The heating of the surface of the rock by the sun expands it, and since the outer part is heated and expanded more than that below, a strain is set up between the superficial part and that below, and this strain may be enough to break off the outer part. “Shell-

ing off" is frequently seen in the boulders of the field (Fig. 13) and on the slopes of the hills and mountains (Fig. 14). Quick and great changes of temperature are more important than slow and slight ones in rock breaking. Thus annual changes are of little consequence, as compared with daily changes. If the changes of temperature involve a range above and below the freezing point of water, they may be still more effective, for if the pores and cracks of the rock are full of water, its expansion on freezing may



Fig. 14.—Exfoliation on the slope of a granite mountain near Royal Arch Lake, Yosemite Quadrangle. (Turner, U. S. Geol. Surv.)

break the rock. Great changes of daily temperature are found especially in high and dry regions, and it is in such places that rock breaking due to changes of temperature is most effective. Swift streams and waves, especially when they carry rock fragments, may also break up igneous rock which is so situated as to be attacked by these agents of destruction, and the growth of roots in cracks may contribute to the same end. All mechanical disruption of igneous rock leaves the fragments essentially like the original rock in composition.

Chemical disintegration. The silicate minerals which make up the larger part of all igneous rocks are usually complex, chemi-

cally. Not rarely they contain as many as three or four basic elements, in union with oxygen and silicon. It is well known that substances which are complex chemically, are, as a rule, less stable than those of simple constitution. Complex silicates, such as the feldspars, the micas, the amphiboles, and the pyroxenes (p. 80) tend to break up into simpler substances. The chemical changes are helped along by the oxygen, the carbon dioxide (CO_2), and the water vapor of the air, as well as by water after it is precipitated. Some of the simpler changes may be noted.

Oxygen may enter into combination with the iron of a silicate mineral which contains iron. The iron is thus taken out of its silicate combination, and in union with the oxygen forms iron oxide, a simple and stable chemical compound. This process is *oxidation*. Oxidation affects other elements also.

Similarly the carbonic dioxide of the air may enter into combination with the base of a silicate mineral. Thus it enters into combination with the calcium of a mineral which contains calcium, taking the latter out of its combination with silica. The union of the calcium and the carbon dioxide gives rise to calcium carbonate. Magnesium and iron may be taken out in the same way, forming magnesium carbonate and iron carbonate, respectively. This process is called *carbonation* and the carbonates thus formed are simple and stable in composition. The carbonates are more soluble than most other common mineral substances.

Water may enter into combination with mineral matter, and the union is *hydration*. Thus when iron rusts (*oxidizes*), it is not merely oxygen which enters into combination with the iron, but water also. Iron rust is a hydrated oxide of iron.

The changes outlined above may be illustrated by the changes which take place in the decomposition of a complex mineral, such as augite, the composition of which is represented by the formula $2\text{CaO} \cdot 2\text{MgO} \cdot 2\text{FeO} \cdot \text{Al}_2\text{O}_3 \cdot \text{Fe}_2\text{O}_3 \cdot 6\text{SiO}_2$. If to this be added 6CO_2 and $2\text{H}_2\text{O}$, the products, after carbonation and hydration might be expressed thus: $2\text{CaO} \cdot 2\text{MgO} \cdot 2\text{FeO} \cdot \text{Al}_2\text{O}_3 \cdot \text{Fe}_2\text{O}_3 \cdot 6\text{SiO}_2 + 6\text{CO}_2 + 2\text{H}_2\text{O} = 2\text{CaCO}_3 + 2\text{MgCO}_3 + 2\text{H}_2\text{O} \cdot \text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2 + 2\text{FeCO}_3 + \text{Fe}_2\text{O}_3 + 4\text{SiO}_2$.

Oxidation, carbonation, and hydration, involving respectively the addition of oxygen, carbon dioxide, and water, increase the

volume of the mineral matter. The result is that the rock affected crumbles. Thus the iron rust formed on a knife blade crumbles off. So the iron rust formed when oxygen and water unite with the iron in the rock, causes the rock in which the change takes place to crumble, partly because of the expansion involved.

Again, some of the simple compounds, especially the carbonates, formed when the rock decays, are somewhat soluble and may be dissolved and taken away. This tends to make the rock less compact by taking away one of its ingredients.

Oxidation, carbonation, and hydration therefore not only change the chemical nature of the rock, but they change its volume, allow some of its material to be carried off in solution, and in many cases cause it to fall to pieces. The result is decayed rock — or one variety of *rock waste*. It is to be observed that the rock waste which arises from decay is unlike the original rock in composition. Some things have been added, and others taken away. In this respect, the waste sediment arising from decay is unlike that arising from rock breaking.

The products of decay may remain where they are formed, or they may be taken away. If they remain where formed for long periods of time, they may come to make a thick mantle of residual earth. The decayed rock is scores of feet in depth in many places, and hundreds of feet in some places. Chemical decomposition is greatest in warm regions, and the products of decay are least readily removed where there are forests. The products of decay are therefore likely to be deepest in warm, forested regions. They are very deep, for example, in some parts of Brazil.

SEDIMENTATION AND SEDIMENTARY ROCKS

Removal of decayed rock. The breaking-up of igneous rock prepares the way for other processes, for the loose material which results from the disruption may be blown away by the wind, washed away by running water, or moved by any agency which shifts loose materials about on the surface of the earth. If the products of rock disintegration are coarse, they may become *gravel* after being rounded by streams or waves. If the material is finer, say

of the size of small grains, it is *sand*; if still finer, it is *mud* when wet, and *dust* when dry.

Deposition of sediment. When carried by any transporting agency, such as wind or water, rock waste becomes *sediment*, and sooner or later is deposited as such. Some of the material picked up and transported by running water is left at the bases of the slopes of mountains and hills from which it is washed, and some of it is left on the flats through which streams flow; but much of it is carried to the sea and left there. The coarser part of the sediment carried to the sea is left near the shore, and the finer parts are taken farther out. This is seen along many coasts where the gravel of the shore-line grades out into sand, and this into mud as distance from the water's edge increases. Thus it comes about that the coarser materials are more or less perfectly separated from the finer.

When the disintegration of the parent rock is by decay, the fine products are usually of different composition from the coarser. Thus the quartz grains of the granite are generally large enough to be readily seen individually; and as the rock decays, this mineral, already a simple compound, undergoes little change, and the grains remain in the rock waste. By moving water, they are rounded into the sand grains with which we are familiar. On the other hand, the crystals of feldspar, which has a complex composition, decompose into very fine particles (of *kaolin* or clay, $\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2 \cdot 2\text{H}_2\text{O}$) unlike the feldspar in composition, and containing but a few of the elements of the feldspar. Thus it happens that the coarse materials, such as quartz, are chemically unlike the finer materials, such as the clay. Running water and waves assort the materials on the basis of their size; but the result is often the separation of materials which are chemically unlike. Thus beds of sand are accumulated, quite separate from beds of clay. They are separated in deposition because they are unlike physically, but in this case, physical unlikeness goes with chemical unlikeness.

Sediments which result from the mechanical breaking up of the rock are like the original rock in composition. When deposited as sand or gravel, such sediment might have about the same composition as the rock from which it was derived, if there was no

decay. As a matter of fact, some decay usually accompanies mechanical breaking. The sediment which contains some of the feldspar of granitic rock is called *arkose*. Arkose represents incomplete decomposition of the parent rock.

Cementation of sediment into solid rock. After sediments such as gravel, sand, mud, etc., are deposited in the sea or elsewhere, they may be cemented into solid rock by the deposition of mineral matter held in solution in water. This cement binds the pebbles, the grains, and the smaller particles together, much as lime binds sand together in mortar. The cemented gravel makes *conglomerate*, or if the pieces of rock are angular, *breccia*; the cemented sand makes *sandstone*; and the cemented mud makes *shale*. These are common sorts of sedimentary rock. The cementation may take place while the sedimentation is in progress, or at a later time. Conglomerate, sandstone, and shale, made up chiefly of particles derived directly from other rock, are *clastic* rocks. Limestone may be broken up, and its particles redeposited and cemented again into solid rock. Such limestone is *clastic*, and limestone made of broken up shells, coral, etc., might also be regarded as *clastic*. In contrast with igneous rocks, *clastic* rocks are made up of particles of other rock, *particles which were once separate and distinct*, but now bound together by some sort of cement. The original constituents touch one another, but do not interlock, as do the crystals of igneous rock.

When sand, mud, etc., are deposited in the sea, shells of sea animals are frequently imbedded in them. If the shells or their forms are preserved, they make a record of the kinds of life that lived when the sediment was being deposited. If the sediments were deposited in lakes or on land, it is the shells or other relics of freshwater or land life which are found in them. All such relics of past life are *fossils*.

Non-clastic sediments. Not all sedimentary rocks are *clastic*. It has already been noted, in connection with the decay of rocks, that some of the compounds formed when rock decays are soluble. A considerable part of the materials dissolved are carried in solution to the sea. Here some of them are extracted by the animals and made into shells or other hard parts. When the animals die, their

shells and other secretions are left behind. Shells and other secretions of calcium carbonate, cemented together, make *limestone*, the composition of which, when pure, is CaCO_3 . It is thought that most limestone was formed of organic secretions, though this is sometimes questioned. The shells, coral, etc., may or may not have been fragmented before cementation.

Limestone has many varieties. One variety is chalk (p. 82). Again, magnesium may replace the calcium in various proportions.

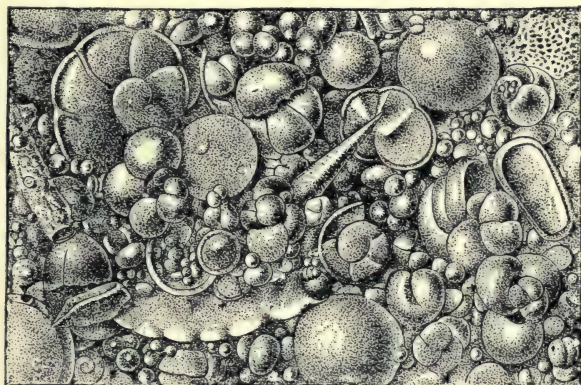


Fig. 15.—*Globigerina* ooze. Magnified 20 times. (Murray and Renard.)

If there is any considerable amount of magnesium, the rock is called *dolomite*. The composition of ideal dolomite would be expressed by the formula CaMgCO_3 ; but the amount of magnesium is variable. There was little magnesium in the shells, coral, etc., out of which much limestone was made. Sometimes the dolomitization of the limestone (the conversion of CaCO_3 into CaMgCO_3) appears to have taken place long after the limestone was formed, while in other cases it appears to have taken place while the material of the limestone was being deposited.

Siliceous deposits. In the decomposition of igneous rocks, a little of the silica, as well as of the bases, is dissolved and carried away in solution. Certain organisms extract this from solution for their tests, shells, etc., just as others extract calcium carbonate. The accumulation of siliceous secretions often forms siliceous rocks.

The *diatom*, *radiolarian*, and other oozes (Fig. 15) of the deep sea are the great examples. Sometimes layers of infusorial earth (*tripolite*) are made up of the secretions of diatoms and other aquatic organisms, accumulated in rather shallow waters. The most familiar examples of indurated rock formed in this way are certain *flints* and *cherts* that occur in limestone and chalk, chiefly as nodules, but sometimes in distinct beds.

Precipitation from solution. Sedimentary rock is formed in still other ways, as by direct precipitation from water which is saturated. Thus *limestone* and *dolomite* might be formed by direct precipitation from water if it became saturated with CaCO_3 and MgCO_3 , and some limestone has been formed in this way. *Rock-salt* has been deposited in thick beds at various times and places, as it is being desposited now about Salt Lake in Utah. The sodium of the salt (composition NaCl) doubtless came from decaying rock, for many igneous rocks contain a little sodium in some complex combination. In the decay of the rock, the sodium is taken out of its complex combination, and made into some soluble compound, and then taken to the sea or to a lake. Its union with chlorine makes common salt. *Gypsum* (CaSO_4) is another form of rock deposited in a similar way. *Iron ore* often occurs in such large bodies that it must be called rock, and some of these bodies of ore are formed by precipitation from solution. Salt, gypsum, limestone, and iron ore are peculiar among rocks, in that but one mineral enters into their composition when they are pure.

Coal is a sort of rock formed by the accumulation of vegetable matter. Some other sedimentary rocks, as noted above, are formed organically, though they can hardly be said to be organic.

The following table gives the principal classes of sedimentary rocks:

Mechanically formed	{	Conglomeratic rocks,— gravel, conglomerate, breccia, etc.
<i>Clastic</i>		Arenaceous rocks,— sand, sandstone, some arkose, etc.
		Argillaceous rocks,— clay, shale, etc., sometime stones.
		Some carbonate rocks, e.g., travertine, siderite.
Chemically formed	{	Chloride rocks,— especially rock-salt.
<i>Non-clastic</i>		Sulphate rocks,— especially gypsum.
		Some siliceous rocks,— some cherts, etc.

Organically formed <i>Non-clastic</i>	{	Calcareous rocks,— most limestones.
		Siliceous rocks,— siliceous oozes, sinter, etc.
		Carbonaceous,— coal, etc.

Original structure of sedimentary rocks. As originally deposited, the gravel, sand, mud, etc., are in beds. The beds may be of different material, or all may be essentially alike. In the



Fig. 16.— Open anticlinal fold, near Hancock, Md. (U. S. Geol. Surv.)

latter case, there are often thin partings of some different material. Thus layers of sandstone may be separated by films of mud, layers of shale by a little sand, etc. These partings may record stages when the water was rougher or quieter than usual, or when it had an excess or a paucity of sediment.

At the time of their deposition, the beds of sediment conformed in a general way to the slope of the bottom where they were deposited. Since the slope of the sea bottom near shore is very gentle as a rule, the beds of sediment are, in most cases, nearly horizontal at the time of their deposition. Their angle of slope is rarely so much as 20° , and is commonly less than 5° .

Secondary structure of sedimentary rocks. Many sedimentary rocks have lost their original position through crustal movements,



Fig. 17.— Closed anticlinal fold, near Levis Station, Quebec. (U. S. Geol. Surv.)

so that beds which were once horizontal now *dip*; that is, they depart from horizontality. The beds

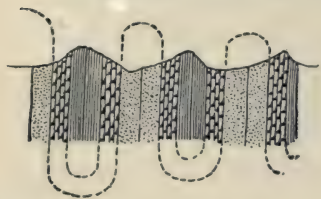


Fig. 18.— Isocline. (Van Hise, U. S. Geol. Surv.)

of sedimentary rock may even be on edge (Fig. 18), having a dip of 90° . The beds of a given region may all dip in one direction, or the dip may change from point to point. They may be folded, and the folds may be open (Fig. 16) or closed (Fig. 17). These diverse positions in which

strata are found are the result of disturbance subsequent to their deposition.

Besides being folded, the beds of sedimentary rock are often *jointed* (Fig. 2) the same as igneous rocks. Slipping may take place along the joint planes, producing *faults* (Fig. 19). The joints of sedimentary rock may be filled by the deposition of mineral matter from solution, making *veins* (Fig. 20). Other secondary

structures of sedimentary rocks will be mentioned in connection with metamorphic changes.

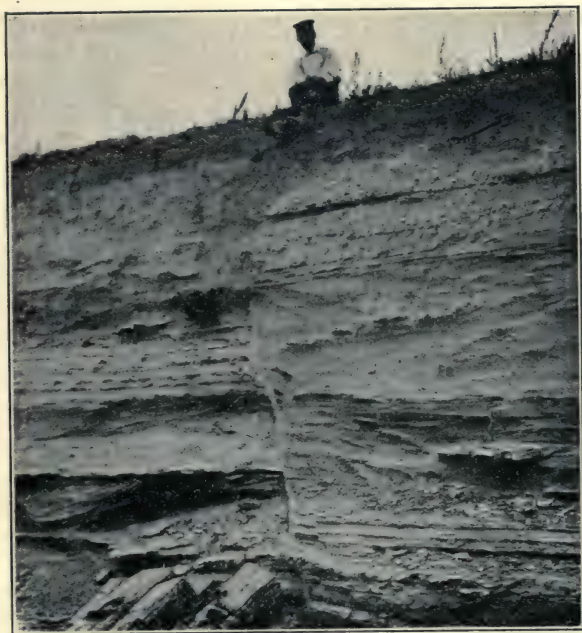


Fig. 19.— Fault in Gering series. Near Rutland Siding (near Crawford), Neb. (Darton, U. S. Geol. Surv.)

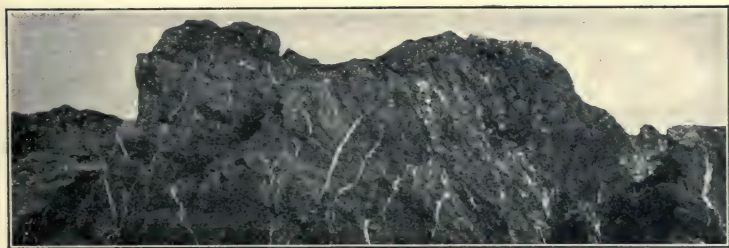


Fig. 20.— Veins of calcite in volcanic tuff. Shore west of Kineraig Point, Elie, Fife. (H. M. Geol. Surv.)

METAMORPHISM AND METAMORPHIC ROCKS

We have already seen that igneous rocks undergo physical and chemical changes, whereby they are disintegrated, giving rise to what has been called *rock waste*; but the waste from one generation of rock is the raw material for rock of a new generation. It is "rock waste" in somewhat the same sense that lumber is forest waste.

Properly speaking, all changes which rocks undergo after being formed are metamorphic changes. According to this view, decayed rock is a phase of metamorphic rock; but it has been customary to limit the term "metamorphic" to those rocks which, instead of being disintegrated by the changes which they undergo, are rendered more compact, more complex in constitution, or more crystalline. Both sedimentary and igneous rocks may be metamorphosed.

Induration of sediments. The first step in the alteration of sediments is their induration, through the aid of cement, pressure, etc. Sandstone and shale are not commonly called metamorphic rocks, but they may be called metamorphosed sand, and metamorphosed mud, respectively. The cementing material of sediment is mineral matter deposited from solution in water. Thus material dissolved at and near the surface may be carried down by descending water, and deposited between the grains of sediment, binding them together. In the process of cementation, a striking plan is often followed, as illustrated by the cementation of sand by silica. It is to be remembered that the common grains of sand are more or less rounded particles of quartz, derived from the imperfect crystals of some rock which contained quartz. The crystallization of quartz, or any other mineral, involves the arrangement of the molecules in some definite way, peculiar to each mineral. When new silica is deposited from solution about these rounded grains of quartz sand, it is always deposited in such a way about each grain as to help to build it out into the form which crystals of quartz always take if free to grow as they will. Microscopic examination of well cemented sandstone often shows the original grains, distinct from the cementing material which appears as additions to original grains (Fig. 21). The enlargement of the

grains may go so far that the spaces between the grains are filled. Sandstone thus changed becomes *quartzite*. Between loose sand at the one extreme, and quartzite at the other, there are all gradations. Quartzite is often regarded as a metamorphic rock, but it is formed by a continuation of the process which cements sand into sandstone.

Grains of other minerals, also, such as feldspar, hornblende, etc., are subject to similar *secondary enlargement*. Important

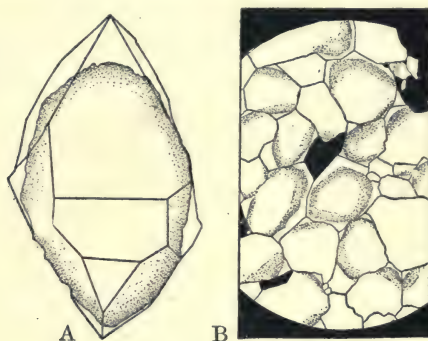


Fig. 21.—A, quartz crystal enlarged by secondary growth. The shaded outline represents the outline of the sand grain; the solid lines, the outline after secondary growth. Magnified 33 diameters. B, sandstone and quartzite texture. The shaded outlines represent the surfaces of the sand grains before growth, the intervening white portions, the added quartz, and the black portions, unfilled spaces. Open spaces characterize sandstone. When the spaces are filled with quartz, the rock becomes quartzite. Magnified 17 diameters. (Van Hise.)

changes in rock are therefore brought about by solution, and then the re-deposition of dissolved mineral matter, through the influence of the water in the rocks. This process might be called *aqueous metamorphism*, because of the important part played by water. Since water is nearly always present in the rocks down to considerable depths, the changes which water produces are wide-spread,—are, indeed, nearly universal, down to the depths to which water penetrates, say five or six miles.

Cavity filling. Cavities in rock larger than pores also receive deposits, if the waters entering them carry mineral matter in solution. The making of *veins* (p. 40) is a case in point. The

agates developed in some cavities afford another illustration. Here the successive layers are commonly silica (chalcedony, p. 76), and differ from each other in color and texture. Before the cavity is entirely filled, the deposit may change from chalcedony to crystals of quartz which grow with their pyramidal points toward the center of the cavity. *Geodes* are examples of a similar process in which the cavity is but partially filled with crystals (Fig. 22). The crystals of geodes are most commonly quartz or calcite, but they may be any other mineral that the waters are capable of depositing. Large cavities lined in this way are known to miners as *vugs*, and these grade into caves with linings of crystals, and with *stalactite* and *stalagmite* (Fig. 23).

When small cavities in rock are filled by material deposited from solution, the result is sometimes called a *secretion*. Crystal-lined cavities (*geodes*, Fig. 22) and agates are examples of secretions. Crystal-lined cavities and veins are the same in principle.

Replacements. In both sedimentary and igneous rocks there are replacements, sometimes resulting in imitative or false forms. Thus the calcium carbonate of corals, shells, etc., may be replaced by silica. This substitution may take place in such a way that the minutest details of structure are preserved. Similarly, woody matter is sometimes replaced by silica, forming silicified or *petrified* wood.

Pseudomorphs. Again, the molecules of one crystal are sometimes replaced by different material, as the molecules of calcite by zinc carbonate, giving a *pseudomorph* of zinc carbonate after calcite. The zinc carbonate takes the form of the calcite, instead of the form which it would take if crystallizing under other circumstances. Hence the name. This sort of change may affect the crystals in any sort of rock.

Concretions. A notable phase of the internal reconstruction of sedimentary rocks is the assembling of matter of the same kind. For instance, silica that was probably deposited in the form of siliceous shells and spicules of plants and animals, and disseminated through the sediments as they were deposited, is later aggregated into nodules of chert or flint (Fig. 24). Similarly, concretions of calcium carbonate or iron carbonate grow in silts



Fig. 22.— Geode. (Bassler, U. S. Geol. Surv.)



Fig. 23.— Deposits of calcite (travertine, stalactites, and stalagmites) in Wyandotte Cave, Ind. (Hains.)

or muds, pressing the clay back as they grow. In many other cases, too, kind comes to kind.

In general, concretions are made by the deposition of mineral matter which was in solution, about a nucleus. The nucleus may be a leaf, a shell, or some bit of organic or inorganic matter. The material of the concretion may come from the immediately surrounding rock, or it may have been introduced from without, likewise by the agency of water. Concretions are generally of matter unlike that of the rock in which they form. Thus concretions of calcium carbonate are common in clay (Fig. 25), con-

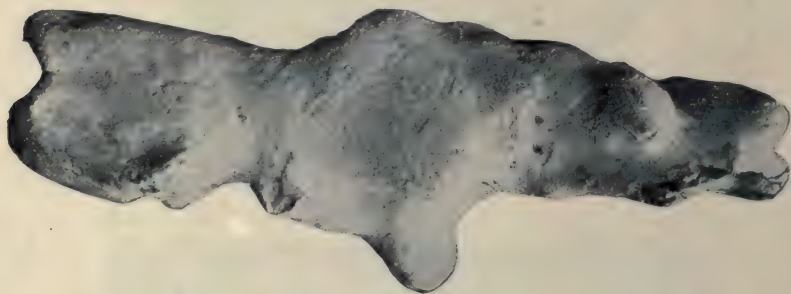


Fig. 24.—Nodule of chert, about half natural size. (Photo. by Church.)

cretions of silica (chert) (Fig. 24) in limestone, and concretions of iron oxide in sandstone (Fig. 26).

Many concretions develop after the enclosing sediment was deposited. This is shown, in some cases, by the fact that planes of lamination may be traced through the concretions. Concretions also form in sedimentary rock during its deposition, and exceptionally, the rock is made up chiefly of them. The chemical precipitates from the concentrated waters of certain enclosed lakes sometimes take the form of minute spherules. From a fancied resemblance of these concretions to the roe of fish, the resulting rock was called *oölite* (Fig. 27). *Oölite* also forms in the open sea under proper conditions. It is now forming about some coral reefs, presumably from the precipitation of lime carbonate temporarily in solution. Some considerable beds of limestone are *oölitic*. The calcium carbonate of such rock may be subsequently



Fig. 25.—Irregular calcareous concretions. Ryegate, Vt. (Photo. by Church.)

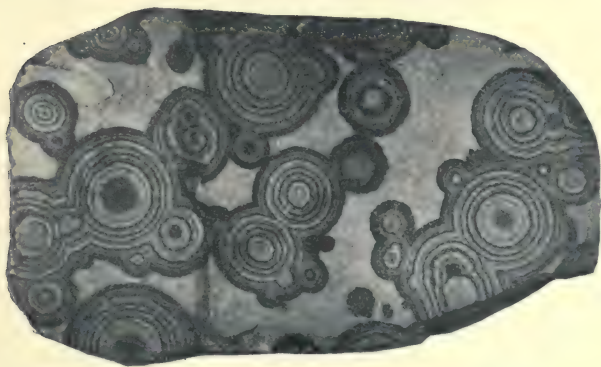


Fig. 26.—Section of spherical concretions, showing rings of ferruginous matter in sandstone; about $\frac{3}{8}$ natural size. (Geikie.)

replaced by silica, leaving the oölitic structure in siliceous rock. Beds of iron ore are likewise sometimes concretionary. Thus there are widespread beds of "flaxseed" iron ore made up of concretions of iron oxide which, individually, resemble the seed which has given the ore its name.

One of the most extraordinary features of some concretions of complex form is their symmetry. This may be of various phases; in exceptional cases there is a bilateral symmetry almost as perfect as in the higher types of animals.

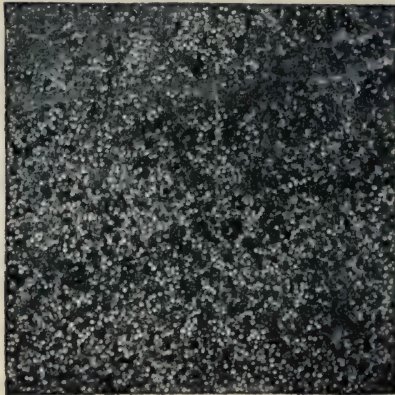


Fig. 27.—Oölitic texture. About natural size. (Photo. by Church.)

Concretions sometimes develop cracks within themselves, and these may then be filled with mineral matter differing in composition or color from that of the original concretions (Fig. 28). Concretions the cracks of which have been filled by deposition from solution, are called *septaria*. They are especially abundant in some of the Cretaceous shales and clays. In not a few cases the filling of the cracks appears to have wedged segments of the original concretion farther and farther apart, until the outer surface of the septarium is made up more largely of vein-matter than of the original concretion. The development of concretions in rock is not commonly looked upon as metamorphism, but it is really a metamorphic change in the broader sense of that term.

In size, concretions may vary from microscopic dimensions to huge masses, 8, 10, or even more feet in diameter. The variations in shape are also great. The conditions of growth have much to do with the form. A concretion which starts as a sphere may find growth easier in one plane than another, when it becomes discoid. Two or more concretions sometimes grow together, giving rise to complicated forms.

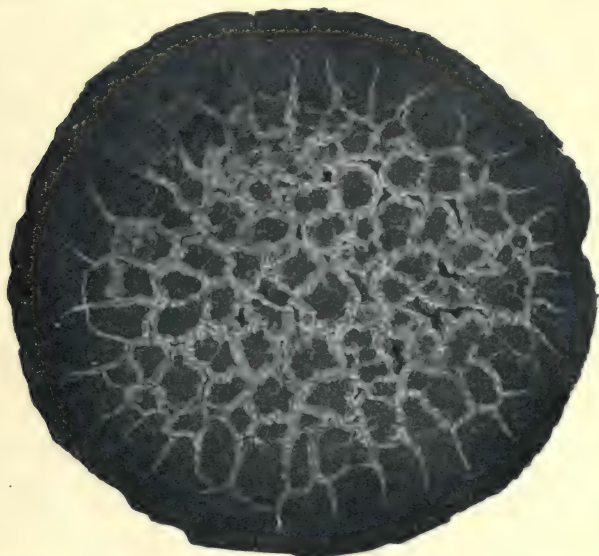


Fig. 28.—Section of a septarian nodule (clay ironstone). About $\frac{3}{8}$ natural size. (Geikie.)

Near the surface, the action of water commonly tends to the decomposition of the rock; but below a few hundred, or at most a few thousand feet, its general effect is to solidify the rock, for at these depths deposition exceeds solution, and oxidation, carbonation, etc., go on much more slowly than near the surface, or not at all. Thus oxidized and hydrated sediments may be buried to great depths, and under the pressure and perhaps the high temperature of these depths, deoxidation and dehydration may take place, with resulting diminution of volume.

Incipient crystallization. A more pervasive metamorphic change in sedimentary rock is incipient crystallization. Some common limestones and dolomites are made up largely of small crystals, though the mass was originally a calcareous mud or ooze. New crystals are also developed in shales and other sediments, out of materials already present, or with such additions as ground-water may make. This process is a kind of incipient metamorphism, and takes place even under ordinary conditions of heat and pressure, through the agency of circulating ground-waters.

Change in chemical composition. Besides simple deposition in pores and cracks, the mineral matter in solution may enter into combination with other mineral matter, giving rise to new, and often to more complex and more compact mineral substances. The changes effected in this way go on slowly, but in the long course of time, they may go so far that none of the original rock material remains in its original condition — all having entered into new combinations. *Soapstone* or *steatite*, for example, is a rock composed essentially of such secondary material. *Serpentine* is a rock made up of a secondary mineral (serpentine) apparently derived from magnesian minerals. *Chloritic rocks* are rocks composed largely of the soft, green, hydrated mineral *chlorite*, derived from the pyroxene, amphibole, biotite, and perhaps other silicates of the parent rock. Other igneous rocks become *talcose* from the development of talc, a very soft, unctuous, hydrous magnesian silicate, developed from the magnesian minerals of igneous rock. All of these rocks may occur in large bodies. All are metamorphic rocks, developed primarily through the chemical rearrangement of the mineral matter of the original rock, with the addition of some matter brought in by ground water, and with the abstraction of some soluble materials from the original rock. The metamorphism may be said to be largely chemical.

By these and similar processes fragmental deposits are solidified into firm rock, and undergo internal changes which reorganize more or less the matter of which they are composed. The process is a very slow one usually, and takes place much more slowly under some conditions than under others. Some of the sands and muds of very early geologic ages are even now imperfectly solidified.

Conditions favoring metamorphism. Besides water, two factors favor the metamorphism of rocks, viz., heat and pressure. Their action gives rise to three general cases, but these blend indefinitely: (1) great heat without exceptional pressure, (2) exceptional pressure without great heat, and (3) great heat and great pressure conjoined. Exceptional heat arises especially from the intrusion of hot lavas, and from pressure. Exceptional pressure arises chiefly from the weight of overlying rocks, and from lateral thrust due to the shrinkage of the globe. Thrust usually gives heat as well as pressure. The water in the rocks not only works changes in them, but greatly facilitates the chemical and mineralogical changes favored by heat and pressure.

Metamorphism by heat. When a mass of lava is poured out upon the surface, it bakes the mantle-rock which it overflows. The extent of the baking depends on the mass of lava and its temperature. The nature of the effect is much the same as in the baking of brick. It consists of *dehydration* of the material, *induration* of the loose matter by welding due to the partial fusion of the particles, and the *development of new compounds*. The time involved is short, the pressure trivial, and the water action limited. If the heat were sufficiently intense, the loose material over which lava flows would be fused; but complete fusion does not usually take place when lava spreads out on the surface.

Intrusions of lava (p. 15) heat the surface above themselves as well as that below. In this case the heat of the lava can only escape through the neighboring rock, and the temperature effects for a given mass of lava are more considerable. Furthermore, the time during which the adjacent rock is hot, and therefore the time during which thermal waters are operative is usually longer than in the case of extruded lavas, and the effects are chemical and crystalline changes, rather than mere baking. The resulting changes are greater the greater the mass of the lava and the higher its temperature. When a vent or fissure is the passageway for lavas that continue to come to the surface for a long time, as in the case of long-lived volcanoes, the rocks which form the walls of the vent are heated for long, and this gives rise to metamorphism through heat, without very unusual pressure, though usually with

the free aid of water. In these cases the chief effects are chemical recombination and crystallization. In the limestones and sandstones the changes are simple, and in the shales more complex. In pure limestones and dolomites little chemical change takes place, but the molecules are rearranged into larger and more perfect crystals, making *marble*. The coarseness of the crystals is a rough sort of measure of the length of time during which the heat acts, and of its intensity, but much depends on the freedom of the attendant water circulation. Crystals an inch or two across are sometimes formed in the zone of contact between the intruded lava and the limestone where the attendant water action is important. If impurities, as silica, alumina, iron, etc., were present in the limestone, various silicate minerals (such as *tremolite* and *actinolite*, p. 74) may be formed in the marble. In pure quartzose sandstones, the effect is to cause the building up of the quartz grains until the interspaces are essentially filled, and the whole becomes a massive *quartzite*. Here, as in the marbles, impurities form adventitious crystals, a very common one being *hematite* formed from the segregation of the ferric oxide of the sandstone.

In the shales, the material to be acted upon is more complex, for, while the main mass is composed of hydrous aluminum silicate, there is usually much free quartz, and often some potash, soda, iron, compounds of calcium, magnesium, etc., for the muds from which shales arise frequently contain not only the fully decomposed matter of the original crystalline rocks, but some fine matter worn from them by wind and water without decomposition. When this mixed matter is acted upon by high heat and moisture, it tends to return to its original crystalline state, so far as its changed composition permits. The result is the development of complex silicates, similar to those of igneous rocks, such as feldspar, mica, hornblende, etc. There is usually a predisposition to form mica in preference to other silicates if the proper constituents are present, and the result is that *mica schists* are common products of the metamorphism of shales by contact with bodies of lava. Mica schists are also formed in other ways, and other schists, dependent on the composition of the shales, are formed about intrusions

of igneous rock. In all such cases pressure probably attends the heat, and is a factor in the development of the schists.

When the change induced by the heat is less considerable, the shale is baked, with incipient re-crystallization, and often takes the form of *argillite*, a compact, massive sort of shale.

Beds of hydrous iron oxide (*limonite*) or of iron carbonate (*siderite*) may be converted by heat into hematite or magnetite. Beds

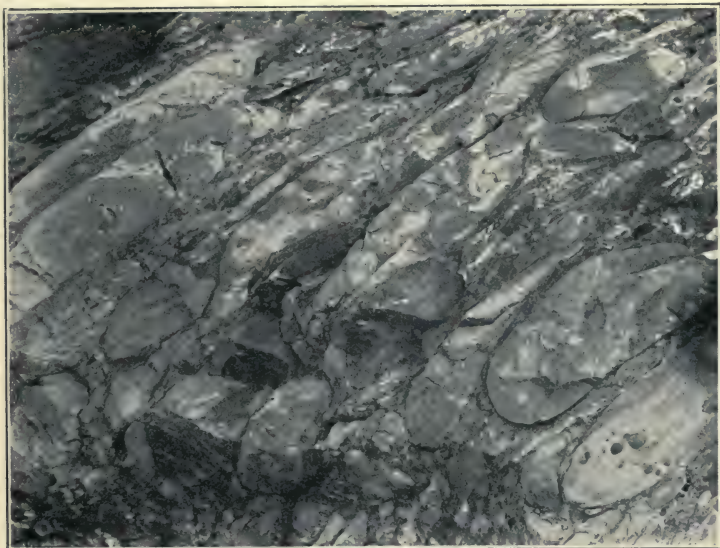


Fig. 29.— Figure showing the elongation of pebbles resulting from pressure. Carboniferous formation, Bancroft Place, Newport, R. I. (Walcott, U. S. Geol. Surv.)

of peat, lignite, and bituminous coal are converted into anthracite by the driving off of the volatile hydrocarbons. If the process goes to the extreme, graphite is the result.

Metamorphism by pressure. Slaty structure. When rocks made up of clastic particles are compressed in one direction, and are relatively free to expand in others, the particles that are already elongated tend to turn so that their longer axes are at right angles to the direction of pressure, and all particles, whether elongate

or not, are more or less flattened at right angles to the direction of stress. This may be readily seen where the particles are large (Fig. 29). As a result of the turning (or *orientation*) and flattening of their particles, rocks so affected split more readily between the elongate and flattened particles, than across them. In other



Fig. 30.—Pre-Cambrian fossiliferous slate. Deep Creek Canyon, 16 miles southeast of Townsend, Mont. (Walcott, U. S. Geol. Surv.)

words, the rocks *cleave* along planes normal to the direction of compression, and break with difficulty and with rough fracture across the planes of cleavage. The condition thus induced is known as slaty structure (Fig. 30), and is best illustrated by roofing-slate, which was originally a mud, later a shale, and finally assumed the slaty condition under strong compression. Sometimes the original bedding may still be seen running across the

cleavage planes developed by pressure (Fig. 31). As the original mud beds were horizontal or nearly so, and as the thrust is most commonly horizontal or nearly so, the induced cleavage commonly crosses the bedding planes at a high angle. If the beds are tilted or bent before the development of the slaty cleavage, the

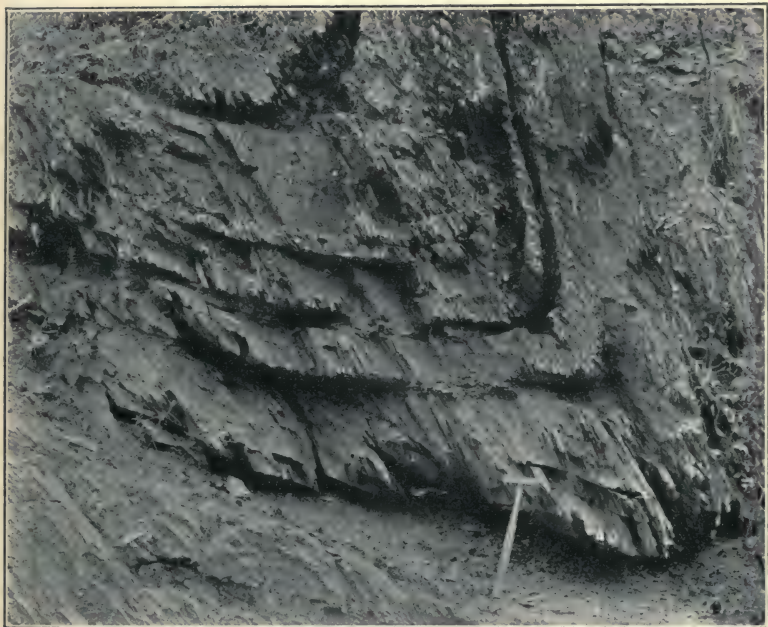


Fig. 31.—Slaty structure and its relation to bedding planes. Two miles south of Walland, Tenn. (Keith, U. S. Geol. Surv.)

angle between the original bedding and the slaty cleavage may be small.

Limestones, sandstones, and conglomerates are not so easily compressed as mudstones, and they usually take on only an imperfect cleavage normal to the direction of pressure.

Foliation, schistosity. More intense pressure in a given direction is capable of breaking down and deforming the most resistant rock. This must necessarily be attended with the evolution of

heat, and thermal effects are mingled with pressure effects, but the thermal effects may be neglected for the moment. The first effect of the compression of such a rock as granite may be to crush it. It then becomes granular or fragmental, and is really a peculiar species of elastic rock (*autoclastic*). By further compression, the fragmented material may be pressed into layers or leaves, much

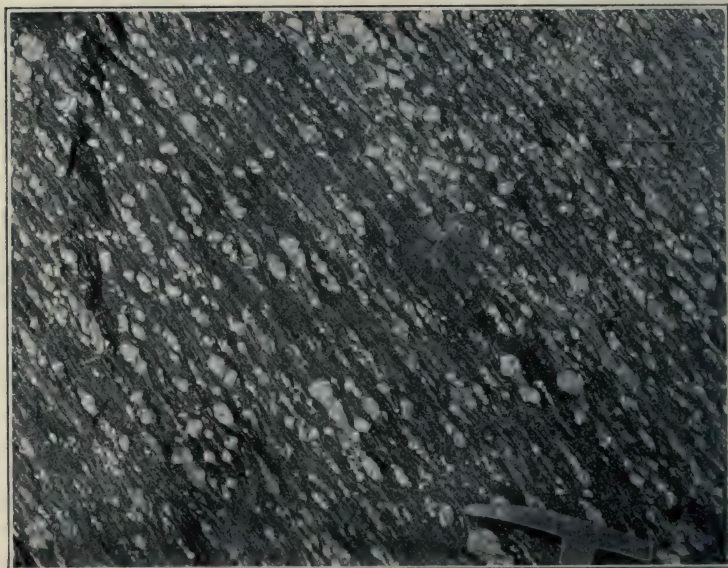


Fig. 32.—Porphyry rendered schistose by pressure. Near Green Park, Caldwell Co., N. C. (Keith, U. S. Geol. Surv.)

as in the development of slaty cleavage; but as a result of the nature of the material, the cleavage is less perfect. This is often attended by more or less shearing of the material upon itself. The result is a *foliated* or *schistose structure* (Fig. 4). A foliated structure may be developed thus in even the most massive rocks. Thus a granite may be transformed into a *gneiss* — which is like a granite in composition, but has a foliated structure; or a basalt may be converted into *schist*, a common term for foliated crystalline rocks. Porphyritic rock rendered schistose by pressure is shown in Fig. 32.

Metamorphism by heat, pressure, and water. The mechanical results produced by pressure are always attended by the evolution of heat, and the heat and the pressure, in the presence of water, which is almost always in the rocks, greatly facilitate chemical changes. The result is that the mineral matter of the crushed and heated rock is often re-combined and re-crystallized. Under pressure, the new crystals arrange themselves so that their longest diameters are at right angles to the greatest pressure, and this orientation of the new crystals, like the orientation of other particles, helps to develop schistosity.

It is to be observed that two distinct processes may be involved in the making of schists. The one is the metamorphism of clastic rocks into crystalline schists, which may be regarded as an up-building process; the other is the mashing down of massive crystalline rocks into schists, which may be regarded as a descensional process. As a rule, neither process goes on alone in the development of schists. In both, there is more or less solution and re-arrangement of the molecules, and in both there is probably something of crushing.

The kind of schist produced depends on the constitution of the rock metamorphosed. Thus basic rocks give rise to basic schists, and acidic rocks to acidic schists. It is obvious that ordinary shales cannot usually become basic schists, because in the production of the muds from which the shales are made, the bases were generally removed; but when shales are highly calcareous and magnesian, as when they grade toward limestone and dolomite, they may become basic schists (*say hornblendic schists*) by metamorphism. It is obvious that limestone and sandstone must retain largely their distinct composition.

Completion of the rock cycle. The crystallizing processes of metamorphism are fundamentally similar to the processes by which rocks crystallize from lavas; but in metamorphism, the work is done chiefly by the aid of an aqueous solution, while in the solidification of lavas the crystallization is from a mutual solution of the constituents in one another, where water was but an incident.

VARIOUS CLASSIFICATIONS AND NOMENCLATURES

From the foregoing sketch of the processes of rock-making it may be inferred that the varieties of rocks may be almost unlimited, and that they may be defined, named, and classified on many different bases; for example:

(1) If the *mode of origin* is chiefly in mind, rocks may be classed as *igneous* (lavas, tuffs, etc.); *metamorphic* (schists, gneisses, anthracite, etc.); *aqueous* (water-laid sediments, travertine, etc.); *colian* (dunes, loess in part); *glacial* (till, moraines); *clastic* (mantle-rock, sandstone, conglomerate, etc.); *organic* (peat, lignite, coal, etc., and indirectly, limestone, chalk, infusorial earth, etc.); and so on.

(2) If the *textural characters* are in mind, rocks are designated vesicular (pumice, scoria, etc.); glassy (obsidian); porphyritic (distinct crystals in obscure matrix); granitic (distinctly grained); compact, porous, earthy, arenaceous (sandy), schistose, etc.

(3) If the *chemical composition* is chiefly regarded, they may be classed as siliceous, calcareous, carbonaceous, ferruginous, etc.; or, if the *chemical nature* is considered, they are grouped as acidic, basic, or neutral.

(4) If the *crystalline character* is made the basis, they are designated phanerites (crystals distinct), aphanites (crystals very small), and amorphous (non-crystalline).

(5) If attention is fastened on *certain ingredients*, rocks are characterized as quartzose, micaceous, chloritic, talcose, pyritiferous, garnetiferous, etc.

(6) When rocks are regarded as *mineral aggregates*, the aggregates may be simple or complex. If simple, they are named from the dominant minerals, as dolomite, hornblendite, garnetite, anorthite, etc.; if complex, they take special names, as syenite, gabbro (p. 29), etc.

(7) When the point of view is *structure of the mass*, they are classed as massive, stratified, shaly, laminated, slaty, foliated, etc.

(8) When *physical state* and *genesis* are considered, they are grouped as clastic, fragmental, or detrital (conglomeratic, brecc-

ciated, arenaceous, argillaceous, etc.); or pyroclastic (tufaceous, agglomeratic), etc.

As sometimes one of these characteristics and sometimes another is most important in a given rock or in a given study, no one classification is satisfactory in all cases, yet each has its advantages in particular cases.

A New System of Classification and Nomenclature

The familiar systems of classifying and naming rocks, if indeed they can be called systems, have grown up gradually out of earlier and cruder methods, many of which were inherited from popular usage. Most of the names and definitions came into use before modern methods of study were adopted. These systems, therefore, retain many crudities and inconsistencies, and lack adaptation to present needs and knowledge. They are too complex and difficult for field use and for general discussions, while not sufficiently exact and systematic for the more rigorous petrological discussions. A more adaptive and consistent system is needed, and in response to this need, a new system of classification of igneous rocks has been offered by a group of leading American petrologists.¹ To some extent this proposed system may be extended to the metamorphic crystalline rocks, with necessary modifications and additions. The classification and nomenclature of the secondary rocks must probably always remain variable and plastic, to express the various points of view which it is desirable to take.

During the transition to this or some other new system, which seems inevitable, the appended alphabetical reference lists of the most common minerals and rocks, with brief definitions in accordance with current usage, will be found serviceable.

The proposed system includes two parts, a *field system* and a *quantitative system*, the one applicable to rocks on casual inspection, and the other, only after detailed study. The field system only is here outlined.²

The proposed field system. The proposed field names are based largely on *texture* and *color*. The mineral constituents are used for subdivisions when they can be determined; otherwise they are neglected.

Classifying chiefly on the basis of texture and crystalline state, there are three groups: *Phanerites*, in which all the leading mineral constituents can be seen without a lens; *aphanites*, in which all, or at least an appreciable part of the constituent minerals cannot be distinguished by the unaided eye; and *glasses*, in which the material is wholly or largely vitreous.

¹ Cross, Iddings, Pirsson, and Washington. *Quantitative Classification of Igneous Rocks*.

² For a statement of the quantitative system reference should be made to the original work mentioned in the preceding foot-note. An abbreviated statement appears in the larger work of the present authors, Vol. I, p. 454, et seq.

I. The *phanerites* may be further classified by their chief mineral constituents as follows:

1. *Granites* (f. n.)¹, consisting largely of *quartz* and *feldspar* of any kind, with or without mica, hornblende, pyroxene, or other minerals. This differs from the present common use in not regarding mica as an essential constituent, and in not distinguishing between alkali feldspars and calcic feldspars. The term therefore includes more than the term as heretofore used.

2. *Syenites* (f. n.), consisting predominantly of *feldspar* of any kind, with subordinate amounts of hornblende, mica, or pyroxene, but with little or no quartz. This differs from the common use in giving hornblende a subordinate place, and in embracing rocks with calcic feldspars.

3. *Diorites* (f. n.), consisting predominately of *hornblende* and subordinately of *feldspar* of any kind, with which there may be mica, pyroxene, or other minerals. This is nearly the present use, except that any kind of feldspar may be the subordinate mineral.

4. *Gabbros* (f. n.), consisting predominantly of *pyroxene* and subordinately of *feldspar* of any kind, with or without other minerals. This nearly coincides with one of the various present uses of the term except that the range of the feldspar is increased.

5. *Dolerites*² (f. n.), consisting predominantly of any *ferromagnesian mineral* not distinguishable as hornblende or pyroxene, with subordinate amounts of *feldspar* of any kind, and with or without other accessory minerals. A name to be used when the dominant mineral is clearly ferromagnesian, but cannot be satisfactorily identified by the eye, as either hornblende or pyroxene, although it may be probably one of these. In other words, the dolerites (deceptive) embrace the whole diorite-gabbro group when too obscure for separation.

6. *Peridotites*, consisting predominantly of *olivine* and *ferromagnesian minerals without feldspar*, or with very little.

7. *Pyroxenites*, consisting essentially of pyroxene without feldspar or olivine.

8. *Hornblendites*, consisting essentially of hornblende without feldspar or olivine.

II. The *aphanites* may be *non-porphyrific* or *porphyritic*.

(a) Non-porphyrific aphanites, when light-colored, may be classed as *felsites*; when dark-colored, as *basalts*.

(b) The porphyritic aphanites or *porphyries*, when light-colored, are *leucophyres*; when dark-colored, *melaphyres*. They may be classified further, according to the kind of phenocryst (distinct crystal) imbedded in the aphanitic ground-mass, as

Quartz-porphyries, or *quartzophyres*;

¹ The initials f. n. (field names) are introduced to show that the term is used in the broad field sense proposed.

² Added by the authors of this work.

Feldspar-porphyrries, or felsophyres (not felsophyres);
Hornblende-porphyrries, or hornblendophyres; and so on.
These may be subclassed by color, as
Quartz-leucophyres, light-colored quartz-porphyrries;
Quartz-melaphyres, dark-colored quartz-porphyrries;
Feldspar-leucophyres;
Feldspar-melaphyres; and so on.

III. The *glasses* are classified, according to color and luster, into *obsidians* or *pitchstones* when dark and lustrous; *perlites* when a spheroidal fracture gives them a pearly appearance; and *pumice* when greatly inflated by included gases.

In general discussions, it is regarded as serviceable to use the term *granitoids* in a broad generic sense, to include all crystalline rocks of the general granitoid type, including the granites, gneisses, etc. In a similar broad way, the term *gabbroids* may be used to include the dark crystalline rocks in which the ferromagnesian minerals predominate, as the diorites, gabbros, dolerites, peridotites, etc. In this convenient and comprehensive way, two contrasted groups of igneous rocks may be designated. As the *granitoids* are usually acidic and the *gabbroids* usually basic, the grouping represents a broad fact of importance.

STRUCTURAL FEATURES COMMON TO ALL ROCKS

Certain structural features peculiar to one group of rocks or another have been mentioned. Thus stratification is characteristic of sedimentary rocks, columnar structure and massiveness of certain igneous rocks, foliation of many metamorphic rocks, etc. *Joints* also have been mentioned, and they affect all rocks, extending down to unknown, but often to great depths.

Faults. Slipping or displacement sometimes takes place along bedding, joint, or fracture planes, and such slippings are faults. The planes of slipping, the *fault-planes*, may be vertical, or inclined at any angle whatsoever. The angle of departure from the vertical is the *hade*. When the fault has a hade, the slipping may be such that the overhanging side goes down relatively (*gravity* or *normal* fault, Fig. 33), or such that it goes up relatively (*thrust* fault, Fig. 34). The hade may approach or even reach 90°. Thrust faults are developed under lateral pressure. Thus faults developed during the folding of strata by lateral pressure are chiefly thrust faults, as in the Appalachian Mountains. Gravity faults imply

crustal tension — not pressure. They were called normal, because they were supposed to be the most common. The fact seems

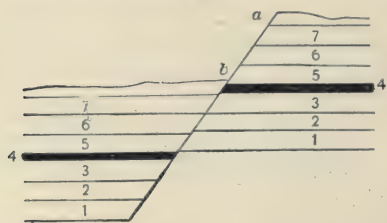


Fig. 33.

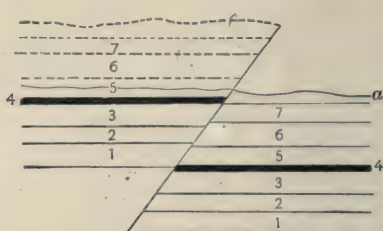


Fig. 34.

Fig. 33.— A normal fault. The overhanging side (to the left) has sunk; *a b* = fault-scarp.

Fig. 34.— A thrust fault. The dotted lines at the left show the portion which has been removed by erosion. The present surface is shown by the line to the left of *a*.

to be that most faults of some regions are gravity faults, and most of those of some other regions are thrust faults; but both types may exist in the same region, though as a rule both types were not



Fig. 35.— A broken (now mended) and offset fence. That in the foreground was formerly in line with the single length directly behind the man. Near Stanford, Cal. (Photo. by Dudley.)

developed in the same region at the same time. The amount of vertical displacement is the *throw* of the fault. The amount of throw occasionally reaches several thousand feet.



Fig. 36.—A topographic map showing a steep mountain slope, which is a fault-scarp, southwest of Honey Lake. Scale, about 4 miles to the inch. (Honey Lake, Cal., Sheet, U. S. Geol. Surv.)

If the slipping takes place between layers, instead of along joint planes, the term *shear* is commonly applied to the movement, but it is in reality a phase of faulting. Such faulting may take

place when the beds are horizontal, or when they dip. When they are horizontal, the direction of the fault-movement is horizontal. The fault-movement may also be horizontal when the plane of slipping is vertical, or when it has any angle of hade. In this case, the fault shows itself at the surface by the displacement of straight lines, such as fences (Fig. 35). The fault at San Francisco in 1906 was of this type.

Where there is vertical movement in faulting, it is not usually possible to say whether the lower side has sunk, or the upper risen, or both, though in normal faults, sinking is probably the dominant



Fig. 37.

Fig. 37.— A branching fault. (Powell, U. S. Geol. Surv.)

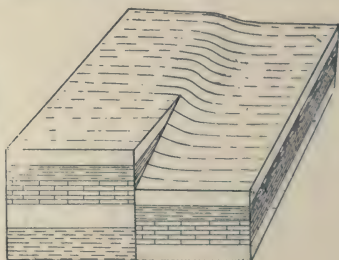


Fig. 38.

Fig. 38.— Diagram of a fault passing into a monoclinial fold.

movement. In any case, one side projects above the other, and the cliff is a *fault-scarp*. In the course of time the scarp is destroyed or obscured by erosion, and most faults are so old that this has taken place; but occasionally fault-scarps of mountainous heights are found, as along the east face of the Sierras, and along some of the basin ranges of Utah, Nevada, etc., but they are much modified by erosion (Fig. 36). Great faults are probably the sum of numerous small slippings distributed through long intervals of time. Faulting is probably the most common cause of earthquakes.

Sometimes a fault branches, and sometimes the faulting is distributed among a series of parallel planes at short distances from one another, instead of being concentrated along a single plane, thus giving rise to a *distributive fault* (Fig. 37).

Faults are observed to die out gradually when traced horizontally, sometimes by passing into monoclinial folds (Fig. 38), and

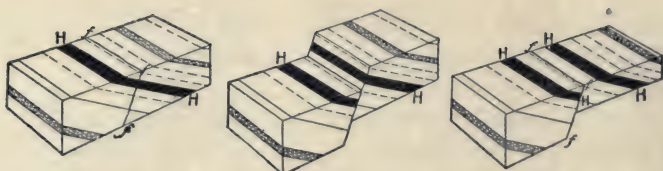


Fig. 41.— Same as Fig. 40, after (1) displacement by a strike fault, and (2) base leveling. The outcrops of certain beds are repeated.

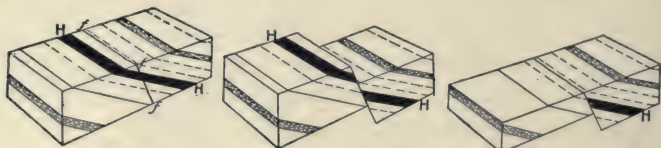


Fig. 42.— Diagram illustrating how a strike fault in such a structure as that shown in Fig. 40, may cause the outcrop of certain beds to disappear.

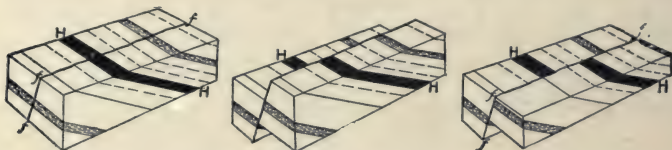


Fig. 43.— Diagram illustrating how a dip fault in the structure shown in Fig. 40 affects the outcrop when the downthrow was on the farther side of the fault-plane.

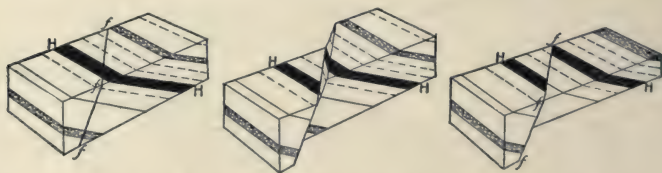


Fig. 44.— Oblique fault in the structure shown in Fig. 40. The downthrow was on the left side. The outcrop of layer *H* is offset with *overlap*.

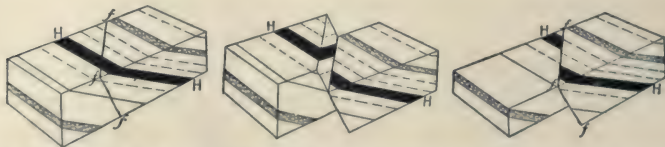


Fig. 45.— Same as Fig. 43, except that the downthrow was on the right side, and the offset is with a *gap* instead of an *overlap*.

throw was to the left, and that shown in Fig. 45 if the downthrow was to the right. In the former case, it is said that there is *offset with overlap*; in the latter *offset with gap*. The amount of the overlap and gap, respectively, increases with the increase of throw

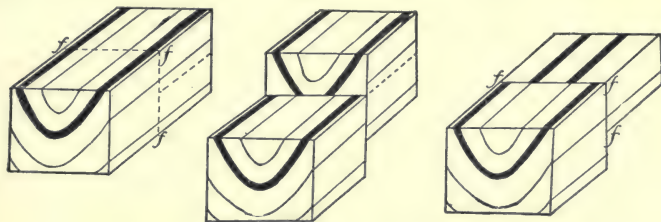


Fig. 46.—Diagram showing effect of faulting on the outcrops of synclinal beds.

and hade, and decreases with increase of dip. In all cases the outcrop (after the degradation of the upthrow side) is shifted down dip.

If a fault crosses folds at right angles to their axes, the effect is to change the distance between the outcrops of a given bed on

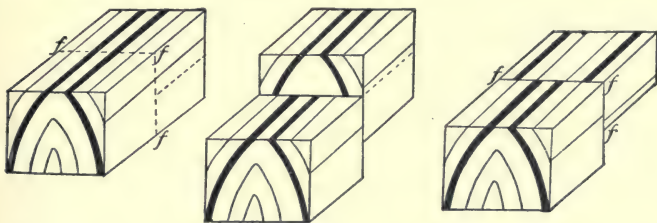


Fig. 47.—Diagram showing effect of faulting on outcrops of anticlinal beds.

opposite sides of the fault, after the truncation of the folded beds. The distance is decreased on the upthrow side of a syncline (Fig. 46) and increased on the upthrow side of an anticline (Fig. 47).

Various other complications arise under other circumstances. Since fault-scarps are not common, the detection and measurement of faults is usually based on the study of the relations of the beds involved, as illustrated by Figs. 41-47.

ORE-DEPOSITS

Ore-deposits are but a special result of the processes already discussed. They have peculiar interest because of their industrial value. An ore is a rock that contains a metal that can be profitably extracted, though for convenience the term is used more broadly to include unworkable lean bodies of ore material. The metal need not preponderate or form any fixed percentage of the whole, for the criterion is solely economic. A gold ore rarely contains more than a very small fraction of one per cent of the precious metal, while high-grade iron ore yields sixty-odd per cent of the metal. In iron ore, the metallic oxide or carbonate makes up nearly the whole rock; in gold ore, the metal is the merest incidental constituent from the petrologic point of view.

All the metals are disseminated through the rock substance of the earth and even throughout the hydrosphere, but they become ores only when concentrated in accessible places to a workable richness. Concentration of the metal is therefore the essential fact in the formation of ores. The degree of concentration required is measured by the value of the metal. The essential elements for consideration are, therefore, (1) the original distribution of the metallic materials through the rocks, (2) their solution by circulating waters (or, rarely, by other means), (3) their transportation in solution to the place of deposit, (4) their precipitation in concentrated form, and (5) perhaps their further concentration and purification by subsequent processes.

The few cases where ore-deposits are made by volcanic fumes or vapors may be neglected here, and only the more common phases of ore-deposition will be considered.

Original distribution of material. The original distribution of ore material through the primitive rocks is beyond the ken of present science, for even the nature of the true primitive rocks is unknown. For present purposes it is sufficient to regard all rocks concerned in ore-deposition as either igneous or sedimentary, and to inquire, first, how far ordinary igneous and sedimentary processes contribute to the segregation of ore material, and second, what the subsequent processes of local concentration are.

Magmatic segregation. In a few instances workable masses of ore (e. g. iron) seem to have arisen by direct segregation in the liquid lava. It is not improbable that the segregation of metallic iron and nickel, and perhaps other metals may be a prevalent process in the deeper parts of the earth, giving rise to such masses of native iron as are found in basalt in Greenland. But masses of metal so segregated presumably gravitate downward, and have little relation to known ore-deposits. It is probable, however, that some segregation of metallic substances in the lavas that come to the surface, is a rather important first step. The rocks thus enriched perhaps determine the places where subsequent concentration is to take place. The acid igneous rocks (p. 24) are, on the whole, perhaps less rich in ore materials than the others; but there is no established law. It is probable that all sorts of lavas were richer in some places than in others at the time of their origin.

Marine segregation and dispersion. In the formation of the sedimentary rocks there was notable metallic enrichment in some cases, and depletion in others. The ground-waters of the land, after their subterranean circuits, carried to the seas various metallic substances in solution. In the main these substances appear to have been widely diffused, and to have been very sparsely deposited through the sediments, for sediments seem to contain less ore material than igneous rocks. But there are important exceptions to this general rule of sedimentary leanness.

The iron-ore beds of Clinton age ranging from New York to Alabama, and appearing also in Wisconsin and Nova Scotia, form a stratum in the midst of the ordinary sediments, and contain marine fossils. The great iron-ore beds of Lake Superior also were sedimentary in origin, and so were most other important iron deposits. It cannot be affirmed, in all cases, however, that the iron deposits were marine. In some cases, the ferruginous material was originally disseminated widely through land rocks, and was concentrated in the course of the sedimentary processes. In other cases it may have been derived from igneous rock rich in iron, extruded beneath water. In either case it is a sedimentary rock, of the non-clastic variety.

Limestone appears to have been enriched locally in lead and

zinc, and more rarely in copper, in the course of its formation. The lead and zinc regions of the Mississippi basin have been regarded as regions of special subsequent enrichment, in areas where there was some enrichment at the time of sedimentation. This enrichment accompanying sedimentation has been attributed to solutions brought into the sea from neighboring lands, and precipitated by organic action in the sea-water.¹ This organic action may have been more effective in some areas than in others, because of the unequal distribution of life and the concentration of its decaying products. It is assumed that such precipitates were at first too diffuse to be of value, and further concentration was required to bring them together into workable deposits.

Metallic material is sometimes concentrated to some extent in sand and mud in the processes of sedimentation, though more rarely. Copper-bearing shale is known, for example, in Germany, Texas, and elsewhere.

Since it is reasonable to suppose that land-waters, on reaching the margins of the water-basins, must occasionally find conditions favorable for the precipitation of their metallic contents, it is inferred that while the processes of sedimentation tended on the whole to leanness, they gave rise to (1) some very important ore-deposits, notably the chief iron ores, the greatest of all ores in quantity and in industrial value, and (2) a diffuse enrichment of certain other areas which made them productive after subsequent processes of concentration, while the sedimentary formations in general were left barren.

Origin of ore regions. From these considerations it appears that for the fundamental explanation of "mining regions" we must look mainly (1) to magmatic differentiation, so far as the country rock is igneous, and (2) to enrichment during sedimentation, so far as the rock is secondary. The subsequent processes in ore making consist in the further concentration of the ore material into sheets, lodes, veins, and similar aggregations by ground-water circulation, or else in the purification of the ores by the removal of useless or deleterious material.

¹Chamberlin. *Geol. of Wis.*, Vol. IV, p. 599, et seq., 1882.

Surface concentration. The simplest of all modes of concentration takes place in the formation of mantle-rock. An insoluble or slightly soluble metallic substance sparsely distributed through a rock may be concentrated to working value by the decay and removal of the principal rock material, leaving the metallic matter in the residuary mantle. The tin ores of the Malay peninsula¹ are examples. Crystals of tin oxide were originally scattered sparsely through granite and limestone, but by the decay and partial removal of the rock, the crystals have accumulated in workable quantities. Certain gold fields and certain iron ores have acquired higher value in the same way; also certain ores of manganese, as those of Arkansas. Such residuary ores may be further concentrated by wash into gulches or alluvial flats, in the course of which the lighter parts of the mantle-rock are largely carried away, and the heavier, including the metal or its compounds, are mainly left behind. Gold placers are the best example. Such concentrates in past ages have in some cases been buried by later deposits, and hence certain ancient sandstones, conglomerates, and mantle-rocks have become ore-bearing horizons.

Purification. A somewhat different mode of concentration and purification has affected certain of the great iron deposits. As already explained, the iron compounds were originally parts of a sedimentary formation, and in beds. In some cases they were sufficiently pure, as first deposited, to be worked profitably; but in most cases they were seriously affected by undesirable mineral associates. After such impure deposits have been subjected to the percolation of waters from the surface for long periods, the impurities, under favorable conditions, are dissolved and taken away, and at the same time, new and valuable materials may be added. The great Bessemer ore-deposits of Lake Superior are examples. Originally impure carbonates or silicates, they have been converted into rich and phenomenally pure ferric oxides by ground-water. Vast quantities of lean ores lie in the tracts not thus purified and enriched. The waters seem to have brought in ferric oxide while they carried away the impurities, especially silica.²

¹ Penrose. Jour. of Geol., Vol. XI, pp. 135-155, 1903.

² Van Hise & Leith, various monographs of the U. S. Geol. Surv.

Solution and re-precipitation. Ore material is often leached out of the surface-rock by water circulating slowly through it, and carried on with the water until it reaches some substance which causes a reaction that precipitates the ore material. This substance may be a constituent of some rock which the circulating water encounters; but more commonly, the precipitation seems to be due to the mingling of waters charged with different mineral substances, the mingling inducing reactions resulting in the precipitation of the ore. Precipitation, however, does not necessarily follow such commingling. It is only when the mingling waters reduce the solubility of the ore material sufficiently, that deposition takes place. Changes of pressure and temperature also may enter into the process.

More concretely stated, the general process of underground ore formation appears to be this: The permeating waters dissolve the ore material disseminated through the rock, and carry it thence into the main channels of circulation, usually the fissures, porous parts, or cavernous spaces. If precipitating conditions are found there, deposition takes place. The precipitating conditions may be merely changes of physical state, such as cooling or relief of pressure, but probably much more generally they consist in the commingling and mutual reaction of waters that have pursued different courses, and are differently mineralized.

Location of greatest solvent action. Since solution precedes deposition, the location of the greatest solvent action may be noted. Water circulation is probably very slight below a depth of two or three miles at most, and above that depth there is little reason for supposing that the rocks of one horizon are more metaliferous than others of their kind. Thus there is no assignable reason why the igneous or sedimentary rocks at the surface are not as rich in ore material as the igneous rocks two or three miles below.

Solvent action is probably greatest where the temperature and pressure are highest, that is, in the deeper reaches of water circulation; but the *amount* of water passing in and out of the deeper zone is small compared with that of higher levels, and the total solvent action is quite certainly much greater in the upper zone than in the lower. At the same time, the solutions in the upper

zone are quite certainly more dilute than those below. The horizon of greatest solution lies quite surely between the surface and a level slightly below the ground-water surface; or, in other words, in the zone where atmosphere and hydrosphere co-operate. Surface-waters are charged with atmospheric and organic acids and other solvents, and their general effect upon the rocks is markedly solvent down to or often below the permanent water-level. In this zone, concentration by residual accumulation may take place, as already noted, if the metallic compounds resist solution; otherwise this zone is depleted of its ore material by solution, and preparation is made for deposition elsewhere.

Solution also continues to take place varyingly as the water descends below this zone of dominant solution, and extends probably to the full depth of water circulation; but in the deeper circuit, precipitation also takes place, and with the waters taking up and throwing down material at the same time, it is difficult to estimate the balance of results. It is probable, however, that the result of these processes is to promote the development of the higher ore values at levels near enough the surface to be accessible, and along the main lines of ground-water circulation.

The influence of contacts. As ore-deposits depend on a dissolving state followed by a depositing state of the waters, and perhaps on a complex succession of these alterations, it is obvious that conditions which favor changes of state and the commingling of different kinds of water, are apt to be favorable to ore production. At any rate it is observed that many important ore-deposits occur at the contact between formations of different character. The contact of igneous rock with limestone is a rather notable instance. It is not to be inferred that such contacts are generally accompanied by workable ore-deposits, but merely that a notable proportion of workable ore-deposits occur at such junctions. It is rational to suppose that where the chemical nature of the two formations is in contrast, the waters that percolate through the one are likely to be mineralized very differently from those that course through the other, and hence that on mingling at the contact, reactions are specially liable to take place, and that when a valuable metallic substance is present, it is liable to be involved and, by chance, to

suffer precipitation. Reactions are the more probable because the contact is likely to be a plane of crustal movement, and hence more or less open and accompanied by fractures, zones of crushed rock, and other conditions that facilitate circulation and offer suitable places for ore formation.

The effect of igneous intrusions. A special case of much importance arises when lavas are intruded into sediments that have previously been partially enriched in the ways above described. The igneous intrusion not only introduces new contact zones, and more or less fracturing, but it brings into play hot waters with their intensified solvent work, their more active circulation, and the reaction between waters of different temperatures. The special efficiency of these agencies is believed to be the determining factor in many cases. Furthermore the intruded lava may be rich in metallic substances, and so be a favorable site for later concentration, and the magmatic waters (waters from the lava) themselves appear to be a source of important ore-deposits. The present tendency is to attach more and more importance to the metallic contents of magmatic waters.

The influence of rock walls. The rock walls themselves are thought sometimes to be a factor in the reactions which precipitate ores. It appears that the effect of the wall may be to withdraw a constituent of the passing solution, and destroy its equilibrium in such a way as to cause the precipitation of the metallic constituent. Once deposited on the walls, ore aids the further accretion of ore of the same sort. The effect of the rock wall here noted is sometimes called *mass action*.

The special forms which ores assume in deposition, as beds, veins, lodes, stockworks, disseminations, segregations, etc., are chiefly incidental to the local situation in which the essential chemical or physical change takes place.

REFERENCE LIST OF THE MORE COMMON ROCK-FORMING MINERALS, AND A FEW OF ECONOMIC IMPORTANCE

Actinolite. A magnesium-calcium-iron amphibole (q. v.); commonly bright green to grayish green; crystals usually slender or fibrous.

Agate. A banded or variegated chalcedony quartz, (q. v.).

Alabaster. A fine-grained variety of gypsum (q. v.), either white or delicately colored.

Albite. A soda feldspar (q. v.), an aluminum-sodium silicate; H.¹ 5-6; cleavage perfect in two planes; luster vitreous or pearly white; occasionally bluish gray, reddish, greenish; sometimes opalescent.

Amethyst. A variety of quartz or corundum of purple or bluish-violet color, due probably to manganese.

Amphibole. The type of an important group of rock-forming minerals known as the amphibole or hornblende group; a ferromagnesian silicate; monoclinic; H. 5-6; luster vitreous to pearly; fibrous varieties often silky; black, ranging through various shades of green to light colors; embraces the magnesium-calcium varieties, tremolite and nephrite; the magnesium-calcium-iron variety actinolite; the aluminous-magnesium-iron-calcium variety *hornblende*, the most important member of the group, and others.

Andesine. A plagioclase feldspar (q. v.); a sodium-calcium-aluminum silicate, intermediate in composition between albite and anorthite; H. 5-6; white, gray, grayish, yellowish, flesh red; luster subvitreous, inclining to pearly.

Andalusite. An aluminum silicate; luster vitreous; whitish, rose red, flesh red, variety pearly gray, reddish brown, olive-green; H. 7.5, infusible; impurities sometimes so arranged in the interior as to exhibit a colored, crossed, or tessellated appearance in cross-section (chiastolite).

Anhydrite. A calcium sulphate; H. 3-3.5; luster pearly to vitreous; white, sometimes bluish or reddish; differs from gypsum in absence of water and in its greater hardness.

Anorthite. A plagioclase feldspar (q. v.); a calcium-aluminum silicate; varies much by impurities and admixtures; H. 6-6.5; pearly or vitreous luster; white, grayish, reddish.

Anthracite. Hard coal; hydrocarbon with impurities; supposed to be derived from bituminous coal by metamorphism.

Apatite. Essentially calcium phosphate with chlorine or fluorine; hexagonal; H. 5; luster vitreous or sub-resinous; colors usually greenish to bluish, characterized by a hexagonal form.

Aragonite. A calcium carbonate; differs from calcite in *cleavage*, and in being orthorhombic; H. 3.5-4; luster vitreous or resinous; white, also gray, yellow, green, and violet.

Asphaltum. Asphalt; mineral pitch, bitumen; a natural mixture of different hydrocarbons; odor bituminous; melts at 90 to 100 degrees C.; burns with a bright flame; graduates into mineral tars and through these into petroleum; probably the residue of the latter.

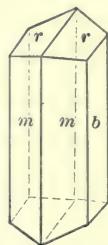


Fig. 48.—
Amphibole
crystal.

¹ H. = Hardness.

Augite. One of the pyroxenes; an aluminum-calcium-magnesium-iron silicate; H. 5-6; monoclinic, crystals usually thick and stout; sometimes lamellar; also granular; black, greenish black, deep green; an important rock-forming mineral.

Beauxite. Essentially hydrated alumina; occurs in concretionary grains of clay-like form, whitish to brown; valuable as a source of aluminum.

Barite. Barites, heavy-spar, barium sulphate; orthorhombic, H. 5-3.5; luster vitreous to resinous, sometimes pearly; white, inclining to yellow, gray, blue, red, or brown; very heavy, sp. gr. 4.3-4.7.

Biotite. Black mica, a potash-aluminum-magnesium-iron silicate; monoclinic; easy basal cleavage into thin laminae; sometimes occurs as a massive aggregation of cleavable scales; H. 2.5-3; luster splendid on cleavage surface; black to dark green; cleavage surfaces smooth and shining; a very common constituent of crystalline rocks.

Bitumen. The same as asphaltum (q. v.).

Calcite. Calcspar; calcium carbonate; rhombohedral, perfect rhombohedral cleavage; often taking the forms known as dogtooth spar, nail-head spar; frequently stalactitic and stalagmitic; H. 2.5-3.5; luster vitreous; white, occasionally pale shades of gray, red, green, blue, violet, yellow, brown; strong double refraction; embraces variety called Iceland spar; a very common mineral; the essential basis of limestone.

Chalcedony. A crypto-crystalline variety of quartz having a wax-like luster, either transparent or translucent; white, grayish, pale brown to dark brown, black, sometimes delicate blue, occasionally other shades; frequently occurs as the lining or filling of cavities, taking on a botryoidal or mamillary form.

Chlorite. The type of an important group of secondary minerals usually characterized by a green color, softness, and smoothness or unctuousness of feeling; they are usually aluminum-magnesium-iron silicates, with chemically combined water; derived from several other species, as pyroxene, amphibole, biotite, garnet, etc.; embraces a number of species, among which are clinochlore, penninite, prochlorite, and delessite.

Chrysolite. Olivine; essentially a magnesium-iron silicate; orthorhombic; H. 6-7; luster vitreous; green, commonly olive-green, sometimes yellow, brownish, grayish green; highly infusible; a common constituent of certain basic igneous rocks; the name olivine is more commonly used by geologists.

Corundum. Alumina; an oxide of aluminum; H. 9; rhombohedral; large crystals usually rough; luster vitreous; color blue, red, yellow, gray, and nearly white; purer forms of fine colors are *sapphires*; the red variety is *ruby*, the yellow, oriental *topaz*, the green, *emerald*, and the purple, *amethyst*; dark colors, with iron oxide, *emery*.

Diallage. A variety of pyroxene (q.v.); H. 4; characterized by thin folia; usually grayish green to grass-green, or deep green; luster on cleavage

surface pearly, sometimes metalloid or brassy; an essential mineral in the gabbros, as sometimes defined.

Enstatite. One of the pyroxenes; essentially a magnesium silicate; orthorhombic; H. 5.5; luster a little pearly on cleavage surface; metalloid in the bronze variety (bronzite); grayish white, yellowish white, greenish white to olive-green and brown; very infusible; a common mineral in certain basic crystalline rocks.

Epidote. A complex aluminum-calcium-iron silicate of varying composition; monoclinic; H. 6-7; luster vitreous, pearly, or resinous; color usually pistachio-green, or yellowish green to brownish green; common in many crystalline rocks, usually as a secondary product.

The **feldspars** are aluminum silicates, with either potassium, sodium, or calcium, or two or more of these; crystal systems, monoclinic and triclinic; possesses distinct cleavage in two directions; H. 6-6.5; range in color from white through pale yellow, red, or green; and occasionally dark; triclinic feldspars frequently called *plagioclase*; the group embraces orthoclase, microcline, albite, oligoclase, andesine, labradorite, anorthite, and numerous varieties.

Fluorite. Fluorspar; calcium fluoride; isometric, usually cubic; H. 4; luster vitreous, sometimes splendent; white, yellow, green, rose, crimson red, violet, sky-blue, and brown; yellow, greenish, and violet most common; occurs usually in veins or cavities in beautiful crystalline form.

Galenite. Galena; lead sulphide; isometric, usually cubic; perfect cubic cleavage; luster metallic; lead-gray; a common ore of lead; occurs in veins and layers, also as linings of cavities.

Garnet. A complex silicate of varying composition, embracing aluminum, calcium, magnesium, chromium, iron, and manganese, but usually only two or three of these are present in abundance, and the varieties are characterized by the leading constituent; isometric, usually in dodecahedrons or trapezohedrons; H. 6.5-7.5; luster vitreous to resinous; commonly red or brown, sometimes yellow, white to blue, green or black; common in mica schist, gneiss, hornblende schist; also in granite, syenite, and metamorphosed limestone.

Glaucanite. Green-sand, a hydrous potassium-iron silicate usually impure, amorphous, or earthy; dull olive-green or blackish, yellowish, or grayish green; opaque, commonly occurs as grains or small aggregations.

Graphite. Plumbago, black lead; a form of carbon, usually impure; rhombohedral, but rarely appearing as a crystal; more often as thin laminae

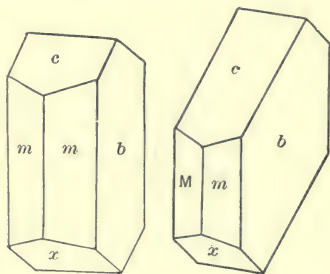


Fig. 49.—Feldspar crystals.

of greasy feel; yields a black adhesive powder; hence its common use for lead pencils; occurs in granite, gneiss, mica schist, crystalline limestone; sometimes results from alteration of coal by heat; occasionally occurs in basaltic rocks and meteorites.

Gypsum. A hydrous calcium sulphate; monoclinic; perfect cleavage into smooth polished plates; occurs in a variety of forms, including fibrous and granular; H. 1.5-2; luster pearly and shiny; white, sometimes gray, flesh red, yellowish, and blue; impure varieties dark; crystallized varieties include selenite, satin-spar, alabaster, etc.; easily recognized by its softness and want of effervescence with acids; occurs in beds; calcined and ground, constitutes plaster of Paris.

Hematite. Ferric oxide, Fe_2O_3 ; iron sesquioxide; rhombohedral, more commonly columnar, granular, botryoidal, or stalactitic; luster metallic, sometimes earthy; iron-black, dark steel-gray, red when earthy; gives red streak or powder; a leading iron ore, 70 per cent metallic iron when pure; the chief source of the red color of soils and rocks generally.

Hornblende. The most important amphibole (q. v.); name sometimes used as a synonym for amphibole.

Hypersthene. One of the pyroxenes (q. v.); a ferromagnesian silicate; orthorhombic; H. 5-6; luster somewhat pearly on cleavage; surface often iridescent; dark brownish green, grayish, or greenish black and brown; a frequent constituent of crystalline rocks.

Iceland spar. A form of transparent calcite (q. v.)

Ilemnite. A titanium iron-oxide; rhombohedral; resembles hematite; luster submetallic; iron-black; powder black or brownish red; occurs frequently in crystalline rocks associated with magnetite.

Iron pyrites. Pyrite (q. v.).

Kaolin. Kaolinite; essentially a hydrous aluminum silicate; usually in clay-like or earthy form; white or grayish white; often tinged with impurities; commonly arises from decomposition of aluminous silicates, especially the feldspars; basis of pottery and china.

Labradorite. A plagioclase feldspar; essentially an aluminum-calcium-sodium silicate; composition intermediate between that of albite and anorthite; triclinic; H. 6; luster pearly or vitreous, gray, brown, or greenish; sometimes colorless or white; frequently shows play of colors; important constituent of various crystalline rocks, especially of the basic class; usually associated with a pyroxene or amphibole.

Leucite. Essentially an aluminum-potassium silicate, allied to the feldspars; H. 5-6; luster vitreous, white, ash-gray, or smoke-gray; occurs in certain volcanic rocks, particularly lavas of Vesuvius.

Limonite. Brown hematite, ocher; a hydrous iron oxide; commonly earthy; also concretionary, stalactitic, botryoidal, and mamillary, with fibrous structure; H. 5-5.5; luster silky, sometimes submetallic, but commonly dull and earthy; brown, ocherous yellow; streak and powder yellowish

brown; constitutes ocher, bog-ore, ironstone, etc.; is the chief source of the yellow color of soils and rocks; arises from the alteration of other iron ores.

Magnesite. Magnesium carbonate; rhombohedral; white, yellowish, grayish white to brown; fibrous, earthy, or massive; found in altered magnesium rocks.

Magnetite. Magnetic iron ore; iron oxide, Fe_3O_4 ; octahedral or dodecahedral; strongly magnetic; H. 5.5-6.5; abounds in igneous and metamorphic rocks.

Marcasite. White iron pyrites; iron sulphide; same composition as pyrite, which it closely resembles; H. 6-6.5; luster metallic, pale gray, bronze, or yellow; prone to decomposition; disseminated through various rocks, particularly plastic clays containing organic matter.

Mica. The type of an important group of rock-forming minerals well known for their perfect cleavage into thin elastic laminæ; among the leading varieties are the common potassium mica (muscovite), the sodium mica (paragonite), the lithium mica (lepidolite), the magnesium-iron mica (biotite), the magnesium mica (phlogopite), and the iron-potash mica (lepidomelane).

Microcline. A triclinic feldspar, closely resembling orthoclase in appearance and having the same composition.

Muscovite. Common or potash mica; essentially an aluminum-potassium silicate; H. 2-2.5; monoclinic; remarkable for its basal cleavage; splits easily into exceedingly thin, flexible, elastic laminæ; luster vitreous, more or less pearly or silky; colorless or variously tinged brown, green, or violet; a common mineral in crystalline rocks, particularly in the granites or gneisses.

Oligoclase. A plagioclase feldspar; essentially an aluminum-calcium-sodium silicate which may be regarded as a mixture of albite and a small amount of anorthite; triclinic; luster vitreous, pearly, or waxy; whitish grading into greenish and reddish; H. 6-7; common in crystalline rocks.

Orthoclase. A potash feldspar; essentially a potassium-aluminum silicate; varying by the replacement of the potassium by sodium and less frequently by other substitutions; monoclinic; occurring in distinct crystals and also in cryptocrystalline forms; cleavage planes perfect with pearly luster on cleavage surface; white, gray, and flesh-red, occasionally varying to greenish white and bright green; H. 6-6.5; difficultly fusible; sanidine a glassy variety; a very common mineral, especially in the granites, syenites, and gneisses.

Olivine. Chrysolite (q. v.).

Petroleum. Naphtha; a native mineral oil; a hydrocarbon, commonly believed to arise from organic matter, both animal and vegetable, but held by some to be due to deep-seated chemical and thermal action.

Plagioclase. A general term embracing the triclinic feldspars whose two cleavages are oblique to each other; embracing albite, oligoclase, andesine, labradorite, and anorthite (q. v.).

Plumbago. Graphite (q. v.).

Pyrite. Iron pyrites, fool's gold, iron sulphide; isometric; commonly in cubes; H. 6-6.5; luster metallic, splendid, or glistening; pale brass-yellow; occurs widely disseminated throughout a large class of rocks; usually harder and lighter in color than copper pyrites, and deeper in color than marcasite, which has the same composition.

Pyroxene. The type of a large and important group of rock-forming ferromagnesian minerals; varies in composition and embraces a large number of varieties; usually a magnesium-iron-calcium silicate; crystals usually thick and stout, but varying greatly; sometimes lamellar and fibrous; H. 5-6; luster vitreous inclining to resinous; green of various shades verging occasionally towards light colors, more often to browns and blacks; among the minerals belonging to the pyroxene group are augite, bronzite, diallage, diopside, enstatite, hypersthene, and others.

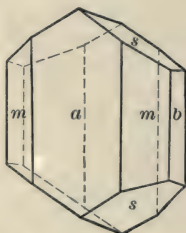
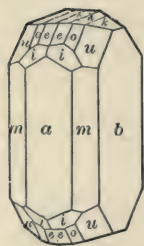


Fig. 50.

Fig. 50. Pyroxene crystals.

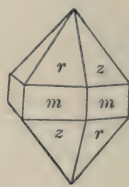
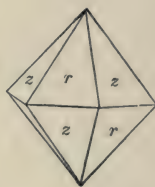


Fig. 51.

Fig. 51.—Quartz crystals.

Quartz. Crystallized silica; hexagonal; crystals commonly six-sided prisms capped by six-sided pyramids; without cleavage; H. 7; hard enough to scratch glass; usually transparent, glassy, colorless when pure; shaded by impurities to yellow, red, brown, green, blue, and black; varieties, *amethyst*, purple or violet; *false topaz*, yellow; *rose-quartz*, *smoky quartz*, *milky quartz*, etc.; *chalcedony* is a cryptocrystalline (crystals not visible) variety; *carnelian*, a red chalcedony; *agate*, a variegated or banded chalcedony; *moss-agate*, a chalcedony containing moss-like or dendritic crystallizations of iron or manganese oxide; *onyx*, chalcedony in layers; *jasper*, an opaque, colored quartz, usually red or brown; *flint*, an opaque impure chalcedony; *chert*, an ill-defined term applied to an impure flinty rock; *hornstone*, a translucent, brittle, flinty rock.

Serpentine. A hydrous magnesium silicate; usually in pseudomorphic forms; also fibrous, granular, cryptocrystalline, and amorphous; H. 2.5-4; luster subresinous to greasy, pearly or earthy, resinous or wax-like; feel, smooth and somewhat greasy; leek-green to blackish green and siskin green verging into brownish and other colors; apparently derived most commonly

from chrysolite or olivine, but also from other magnesian minerals; sometimes constitutes the bulk of rock masses.

Siderite. Iron carbonate; rhombohedral; H. 3.5-4.5; luster vitreous, more or less pearly, ash-gray, yellowish or greenish, also brownish; occurs as extensive iron deposits and in crystalline rocks.

Steatite. Soapstone, a variety of talc (q. v.); hydrous magnesium silicate.

Sulphur. A well-known element occurring native in volcanic regions; also formed by the decomposition of sulphides, particularly pyrites.

Talc. A hydrous magnesium silicate; usually in foliæ; granular or fibrous forms; also compact; easy cleavage into thin flexible laminæ, but not elastic; luster pearly on cleavage surface; apple-green to silvery white; H. 1-2; a secondary product from the alteration of magnesian minerals; distinguished by its soft, soapy feel, soapstone being one variety; whitish form is known as French chalk.

Topaz. An aluminum silicate, with part of the oxygen replaced by fluorine; orthorhombic; H. 8; luster vitreous; colorless, straw-yellow verging to various pale shades, grayish, greenish, bluish, and reddish; distinguished by its hardness and infusibility; occurs in crystalline rock.

Tremolite. A calcium-magnesium amphibole; a common constituent of certain crystalline rocks.

Zeolites. A group of minerals derived from the alteration of various aluminous silicates.

REFERENCE LIST OF THE COMMONER ROCKS¹

Adobe. A fine silty or clayey deposit formed by gentle wash from slopes and subsequent lodgment on flats; especially applied to clayey accumulations in the basins and on the plains of the western dry region.

Agglomerate. An aggregate of irregular, angular or subangular blocks of varying sizes, usually of volcanic origin; distinguished from conglomerate, in which the constituents are rounded.

Alluvium. Sediment deposited by streams.

Amygdaloid. A vesicular igneous rock whose cavities have been filled with minerals deposited from aqueous solutions; the fillings are called *amygdules*, because sometimes almond-like in form.

Andesite. An igneous rock consisting essentially of the plagioclase feldspar *andesine* (sometimes oligoclase) and pyroxene (or some related ferromagnesian mineral); sometimes cellular, porphyritic, or even glassy; usually rich in feldspar microlites.

Anorthosite. A rock consisting mainly of the feldspar labradorite.

¹ The following definitions are given, as nearly as practicable, in accordance with present common usage, which is, however, more or less varying and inconsistent.

Aphanite. A rock whose constituents are so minute as to be indistinguishable to the naked eye; rather a condition of various rocks than the name of any specific rock.

Arenaceous rocks. Either those which are mainly sand, or those in which sand is a notable accessory.

Argillite. A clayey rock; usually applied to hard varieties only.

Arkose. A sand or sandstone formed of disaggregated granite or similar rock in which a notable part of the grains are feldspar or other silicate; sand when undefined, is understood to be quartzose.

Augite. A rock made up mainly of augite.

Basalt. A dark, compact basic igneous rock consisting of a mass of minute crystals sometimes with more or less glassy base, often containing also visible crystals; composed of plagioclase and pyroxene, with olivine magnetite, or titaniferous iron as common accessories; a basic lava in which the crystallization has taken place rapidly; usually rich in crystallites or microlites; graduates into dolerite and basic andesite.

Bituminous coal. Common soft coal, intermediate between lignite and anthracite; contains much bituminous matter, i. e., hydrocarbons.

Boulders. Rounded masses of rock, such as those that have been shaped by glaciers.

Breccia. A rock composed of angular fragments, contrasted with pudding-stone or conglomerate, in which the fragments are rounded.

Buhrstone. A compact, flint-like silicious rock full of small cavities, so named from use as millstones.

Calc-sinter (calcareous tufa). A loose cellular deposit of calcium carbonate made by springs; travertine is the better term, as tufa should be left for volcanic elastics.

Cannel coal. A very fine-grained homogeneous bituminous coal, giving off much gas and burning with a candle-like flame.

Chalk. A fine-grained soft rock composed essentially of calcium carbonate derived from minute marine organisms.

Chlorite schist. A schistose rock in which chlorite is a predominant mineral; usually greenish, whence the name.

Clastic rock. Formed from the debris of broken-down rocks; the same as fragmental or detrital rock.

Clay. A term commonly applied to any soft, unctuous, adhesive deposit, but in strict use confined to material composed of aluminum silicate; many so-called clays are chiefly silicious silts or loams.

Clay ironstone. A clayey rock heavily charged with iron oxide, usually limonite; commonly in concretionary form.

Clinkstone. A name applied to phonolite because of its metallic clinking sound when struck; composed of orthoclase, with nephelite and one or more of the ferromagnesian minerals as accessories.

Chert. An impure flint, usually of light color, occurring abundantly in concretionary form as nodules in certain limestones.

Coal. A carbonaceous deposit formed from the remains of plants by partial decomposition.

Concretions. Aggregates of rounded outlines formed about a nucleus; the material is various: clay, iron ore, calcite, silica, etc.

✓ **Conglomerate** (puddingstone). A rock formed from rounded pebbles; consolidated gravel.

Coquina. A rock formed almost wholly of small and broken shells; especially applied to a shell limestone of Florida.

Dacite (quartz-andesite). An andesite (q. v.) with quartz.

Diabase. A dolerite (q. v.) which has undergone alteration; consists essentially of plagioclase feldspar and augite, with magnetite or titaniferous iron as a common accessory; one of the greenstones.

Diatom ooze. A soft silicious deposit found on the bottom of the deep sea, made largely or partly of the secretions of diatoms.

Diorite. An igneous rock usually of dark-greenish color, consisting of plagioclase feldspar and hornblende; often speckled from the commingling of light feldspar and dark hornblende.

Dolerite. A fine-grained igneous rock composed of plagioclase feldspar (labradorite or anorthite) and augite (or related ferromagnesian mineral, as enstatite, olivine, or biotite), with magnetic or titaniferous iron as common accessories; crystals usually of medium size, assuming the ophitic structure; embraces many of the greenstones; graduates into basalt on the one hand and gabbro on the other.

Dolomite. A magnesian limestone.

✓ **Drift.** In common American usage, a mixture of clay, sand, gravel, and boulders formed by glacial agencies.

Eolian rocks. Deposits formed by wind, embracing especially dunes and much of the loess.

Felsite (felstone). A light-colored aphanitic rock composed of feldspar, often with quartz, in which the crystallization is very imperfect or obscure, giving a close-grained texture with conchoidal fracture and flinty aspect; certain varieties are called petrosilex and hälleflinta.

Fire clay. A clay capable of standing a high degree of heat. The percentage of iron, calcium, magnesium, and the alkalies must be very low. Often found in association with coal.

Flint. A compact dark chalcedonic or lithoid form of quartz.

Freestone. A sandstone of uniform grain without special tendency to split in any direction.

Fulgurites. Glassy tubes, produced through fusion by lightning in penetrating sand, earth, or rock.

Gabbro (euphotide). A crystalline rock composed of the plagioclase

feldspar labradorite (or anorthite), and diallage (or a related ferromagnesian mineral), with magnetite or titaniferous iron as a common accessory.

Gangue. A term applied to the crystalline material in which ores are imbedded.

Ganister. Essentially a quartz silt, pulverized quartz, or silicious fire clay suitable for lining iron furnaces.

Garnetite. A rock composed largely of garnets.

Geyserite. The silicious sinter deposited about hot springs.

Gneiss. A foliated granite, consisting normally of quartz, feldspar, and mica; the feldspar typically orthoclase.

Granite. A granular crystalline aggregate of quartz, feldspar, and mica; the feldspar typically orthoclase; popularly and properly used for any distinctly granular crystalline rock.

Granulite. A fine-grained granite with little or no mica.

Graphic granite. (See pegmatite.)

Greensand. A sand or sandstone containing a notable percentage of grains of glauconite.

Greenstone. A comprehensive term used to designate igneous and metamorphic crystalline rocks of greenish hue and of intricate and often minute crystallization; they are mostly dolerites, diabases, and diorites; a convenient term for field use where the constituents cannot be determined, and for general use when the variety is unimportant.

Greywacke. A sand rock in which the grains are largely basic silicates instead of quartz.

Hornblendite. A rock essentially composed of hornblende.

Hornstone. A very compact, silicious rock of horn-like texture, allied to flint; term also applied to flinty forms of felsite.

Hydraulic limestone. (See waterlime.)

Hypogene rocks. Those formed deep within the earth under the influence of heat and pressure.

Ironstone. A rock composed largely of iron, usually applied to clayey rocks having a large iron content.

Infusorial earth (tripolite). An earthy or silt deposit consisting chiefly of the silicious secretions of diatoms.

Itacolumite. A flexible sandstone whose pliability is due to an open arrangement of sand grains which are held together by scales of mica.

Jasper. A reddish variety of chalcedonic quartz.

Lapilli. Small fragments of lava ejected from volcanoes; volcanic cinders.

Lava. A molten rock, especially applied to flows upon the surface, whether from vents or from fissures; also applied to the solidified product.

Lignite. (brown coal). A soft, brown, impure coal.

Limestone. A rock composed primarily of calcium carbonate, though magnesium sometimes replaces a part of the calcium. (See dolomite and marble.)

Loess. A very fine porous silicious silt containing some calcareous material which often collects in nodules (*Löss Kindchen*) or in vertical tubules; characterized by a peculiar competency to stand in vertical walls; held by some to be eolian, by others to be fluvial or lacustrine, and by still others to be partly eolian and partly aqueous.

Mantle rock. (See regolith.)

Marble. Typically a granular crystalline limestone or dolomite produced by metamorphic action; but the term is variously applied to calcareous and even to other rocks that are colored ornamentally and susceptible of polish.

Marl. An earth formed largely of calcium carbonate, usually derived from the disintegration of shells; or the calcareous secretions of plants, notably the stoneworts; term also sometimes applied to glauconitic and other fertilizing earths.

Melaphyre. A term of varying usage; most commonly applied perhaps to an altered basalt (q. v.), especially an olivine-bearing variety.

Meta-diorite. A term sometimes used for a metamorphic diorite; in like manner *meta* is prefixed to dolerite, syenite, etc.; not in general use.

Meta-igneous rock. A metamorphosed igneous rock.

Metamorphic rock. A rock which has been altered, particularly one which has been rendered crystalline, or recrystallized by heat and pressure in conjunction with water.

Meta-sedimentary rock. A metamorphosed sedimentary rock.

Microgranite. A very fine-grained granite.

Microclites. Incipient crystals found in glassy lavas; usually needle-shaped, or rod-like; occurring singly and in aggregates.

Millstone. (See buhrstone.)

Minette (mica-syenite). A rock consisting essentially of orthoclase and mica, or a syenite in which mica replaces hornblende or predominates over it.

Monzonite. A granitic rock composed of orthoclase and plagioclase in nearly equal proportions, with ferromagnesian minerals; a rock intermediate between syenite and diorite.

Mudstone. Solidified mud or silt, shale.

Nodules. Concretionary aggregations of rounded form.

Novaculite (hornstone, oilstone). A very fine-grained, hard sandstone or siltstone, used for whetstones.

Obsidian. A typical form of volcanic glass usually of the acidic class.

Onyx. A variety of chalcedonic quartz having colored bands alternating with white; the "Mexican onyx" is a crystalline calcium carbonate, variegated with delicate colors due to iron and manganese.

Oölite. A limestone or dolomite composed of small concretions resembling the roe of fish.

Ooze. A soft deposit of the deep sea; characterized usually by a microscopic shells from which it is mainly derived; as diatom ooze, globigerina ooze, etc.

Peat. The dark brown or black residuum arising from the partial decomposition of mosses and vegetable tissue in marshes and wet places.

Pegmatite. A term of ill-defined usage applied to rocks whose grain varies from coarser to finer, and often takes on peculiar aspects due to the simultaneous crystallization and mutual inter-growths of the crystals; graphic granite is a distinct type of pegmatite in which quartz and orthoclase crystals grew together along parallel axes so that cross-sections give figures resembling certain Semitic letters (Fig. 12).

Peridotite. A very basic igneous rock composed chiefly of olivine with augite or related ferromagnesian minerals, with magnetite and chromite as accessories.

Perlite (pearlstone). A form of glassy lava made up in part of small spheroids formed of concentric layers which have a lustrous appearance like pearls.

Phonolite (nephelite-trachyte, clinkstone). A compact resonant igneous rock formed of sanidine and nephelite, with accessories.

Phyllite (argillite). A variety of indurated, partly metamorphosed, clay silt in which finely disseminated micaceous scales are abundant and lustrous; intermediate between typical clay slate and mica-schist.

Pitchstone. A dark vitreous, acid, igneous rock of less perfect glassy texture than obsidian, and more resinous and pitch-like.

Plutonic rocks. Igneous rocks formed deep within the earth under the influence of high heat and pressure; hypogene rocks; distinguished from eruptive rocks formed at the surface.

Porphyry. A rock consisting of distinct crystals embedded in an aphanitic ground-mass, or of large crystals embedded in smaller ones.

Pumice. A glassy form of lava rendered very vesicular through inflation by steam.

Pyroclastic rocks. Fragmental or clastic rocks produced through igneous agencies, embracing volcanic ashes, tuffs, agglomerates, etc.

Pyroxenite. An igneous rock consisting essentially of pyroxene.

Quartzite. A rock consisting essentially of quartz, usually formed from quartzose sandstone by cementation or metamorphic action.

Regolith. A name recently suggested to embrace the earthy mantle that covers indurated rocks, chiefly residuary earths; mantle-rock.

Rhyolite. An aphanitic or partly glassy igneous rock showing flowage lines, usually applied only to the acidic varieties.

Sandstone. Indurated sand usually composed of grains of quartz, but not necessarily so; sometimes contains grains of the various silicates.

Schist. A crystalline rock having a foliated or parallel structure, splitting easily into slabs or flakes, less uniform than those of slate; they are composed mainly of the silicate minerals.

Scoriæ. Light, cellular fragments of volcanic rock, coarser than pumice.

Septaria. Concretions the interior cracks of which have been filled with calcite or other mineral deposited from solution (Fig. 28).

Serpentine. A rock consisting largely of serpentine; derived in most cases by alteration from magnesian silicate rocks.

Shale. A more or less laminated rock, consisting of indurated muds, silts, or clays.

Slate. An argillaceous rock which is finely laminated and fissile, either due to very uniform sedimentation or (more properly) to compression at right angles to the cleavage planes; e. g., common roofing-slate (Fig. 30).

Soapstone (steatite). A soft unctuous rock, composed mainly of talc.

Stalactites. Pendant icicle-like forms of calcium carbonate deposited from dripping water.

Stalagmites. The complement of stalactites formed by calcareous waters dripping upon the floors of caverns.

Steatite. (See soapstone.)

Syenite. A granitoid rock composed of orthoclase and hornblende, or other ferromagnesian mineral; the name was formerly applied to a granitoid aggregate of quartz, feldspar, and hornblende.

Till (boulder clay). A stony or bowldery clay, or rock rubbish formed by glaciers.

Trachyte. A name formerly applied to a rock possessing a peculiar roughness due to its cellular structure; but at present mainly confined to a compact, usually porphyritic igneous rock, consisting mainly of sanidine associated with varying amounts of triclinic feldspar, augite, hornblende, and biotite.

Trap. A general term for igneous rocks of the darker basaltic types.

Travertine. A limestone deposited from calcareous waters, chiefly springs; usually soft and cellular, and hence also called calcareous tufa; calc sinter.

Tuff (tufa). A term including certain porous granular or cellular rocks of diverse origins; the volcanic tuffs embrace the finer kinds of pyroclastic detritus, as ashes, cinders, etc.; the calcareous tufas embrace the granular and cellular deposits of springs; the better usage limits the term to volcanic clastics.

Waterlime. An impure argillaceous limestone possessing hydraulic properties.

Laboratory work. Laboratory study of the common rock-making minerals and of the common types of rocks should be undertaken in connection with this chapter. The *groups* of minerals mentioned on page 26 should be made familiar first. The identification of these minerals in the rocks should follow. The arrangement of the minerals is important in some cases, especially in metamorphic rocks. It is as important to stop these studies at the right point, *in this connection*, as to take them up. The technicalities of mineralogy, and the refinements of rock classification should not be touched at this point. Appropriate limitations for the study of igneous rocks, at this point, are suggested on pages 27-30, and 59-62.

CHAPTER III

THE GEOLOGICAL WORK OF THE ATMOSPHERE

Since the atmosphere is a part of the earth, its activities and its history are proper subjects of geologic study. This view is in no way vitiated by the fact that the special study of the atmosphere constitutes the science of *Meteorology*. The atmosphere is one of the three great formations of the earth, and as a factor in geology, it takes its place beside the hydrosphere and the lithosphere. The study of the atmosphere, so far as taken up in geology, is restricted, commonly, to the effects of the atmosphere on the other parts of the earth; but the origin and history of the atmosphere are surely proper subjects of inquiry, in any thorough-going history of the earth.

The atmosphere has played a part in the history of the earth comparable to that of water, though its record is less clear. Unsubstantial as the atmosphere seems when contrasted with the liquid and solid portions of the earth, its extreme mobility and its chemical activity make it an agent of importance in geological history. It plays and has played a direct part as (1) a mechanical and (2) a chemical agent, and it serves and has long served an indirect function in furnishing the conditions under which (3) the sun produces its temperature effects, and (4) evaporation and precipitation take place. The atmosphere, too, furnishes the necessary conditions for land plants and animals, and the important influences that spring from them.

The atmosphere is not only an agent of decomposition, as already noted in connection with the decay of igneous rock, but it is also one of the great transporting agents of the earth, and helps to carry away the fine material produced by the chemical activity of its elements.

THE MECHANICAL WORK OF THE ATMOSPHERE

The mechanical work of the atmosphere is accomplished chiefly through its movements. A feeble breeze is competent to move particles of dust, a wind of moderate velocity to shift dry sand, and exceptionally strong winds sometimes move small pebbles.

The principal movement of the wind is horizontal; but every obstacle against which it blows deflects a part of it, and some of these deflections are upward. Furthermore, there are exceptional winds, in which the vertical element predominates. Particles of dust are often caught by these upward currents, and carried to great heights, and transported great distances.

Dust¹

Transportation of dust by the wind is nearly universal. No house, no room, and scarcely a drawer is so tightly closed but that dust enters, and the movements of dust in the open must be much more considerable. The visible dustiness of the atmosphere in dry regions during wind-storms is familiar proof of the efficiency of the wind as a carrier of dust.

Under special circumstances, opportunity is afforded for rough determinations of the distance and height to which dust is carried by the wind. Snow taken from snow-fields in high mountain regions is found to contain a small amount of earthy matter. Some of its particles are often volcanic dust, even when the place whence the snow is taken is scores or even hundreds of miles from the nearest volcano. In the great eruption of Krakatoa² in 1883, large quantities of volcanic dust (pulverized lava) were projected to great heights into the atmosphere. The coarser particles soon settled; but many of the finer ones, caught by the currents of the upper atmosphere, were carried around the earth in 15 days. Through all its long journey, the dust was gradually settling from the atmosphere, but not until it had traveled repeatedly round the earth did its amount become so small as to cease to make its

¹ For an excellent study of the erosion, transportation, and sedimentation performed by the atmosphere, see Udden, *Jour. of Geol.*, Vol. II, pp. 318-331; also *Pop. Sci. Mo.*, September, 1896.

² The Eruption of Krakatoa. Committee of the Royal Society, 1888.

influence felt in the historic red sunsets which it occasioned.¹ It is probable that dust from this eruption found its way to nearly all parts of the earth.

Volcanic dust is shot into the atmosphere rather than picked up by it. Dust picked up by the wind is perhaps transported not less widely than volcanic dust, but, after settling, its point of origin is less readily determined. It would perhaps be an exaggeration to say that every square mile of land surface contains particles



Fig. 52.—Vertical face of loess near Huang-tu-Chai in northern Shan-si. (Willis, Carnegie Institution.)

of dust brought to it by the wind from every other square mile, but such a statement would probably involve much less exaggeration than might at first be supposed.

Extensive deposits of dust blown about by the wind are known. Considerable beds of volcanic dust, locally as much as 30 feet thick, are known in various parts of Kansas and Nebraska, hundreds of miles from the nearest known volcanic vents. In China there is an extensive earthy formation, *the loess* (Fig. 52), sometimes reaching a thickness of hundreds of feet, which Baron von Richtofen believed to have been deposited by the wind.² This

¹ A brief account of the influence of the dust on sunsets is found in Davis's *Elementary Meteorology*, pp. 85 and 119.

² Von Richtofen; "China."

conclusion, has however, been questioned. The loess of some other regions has been referred to the same origin, and much of it is quite certainly eolian.¹ From the flood plains of such rivers as the Missouri, clouds of dust are swept up and out over the adjacent high lands at the present time, whenever the surface of the flood plain is dry and the wind strong. This dust is very like loess, if, indeed, it is not loess.

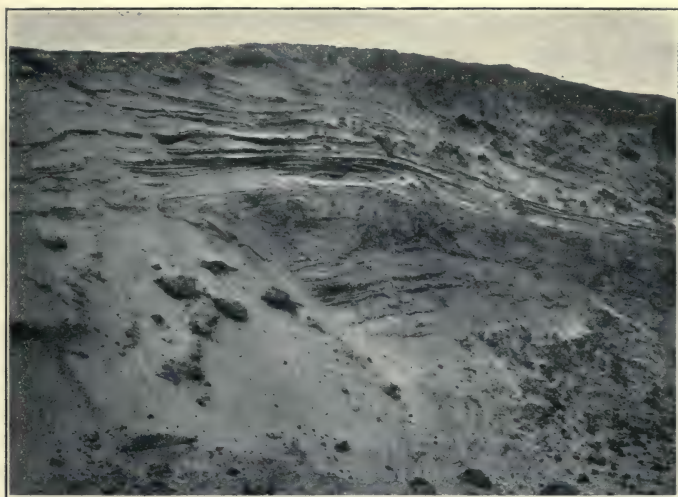


Fig. 53.— Interstratified eolian sand and loess near Milford, Nebraska. (Condra.)

The transportation of dust is important wherever strong winds blow over dry surfaces free or nearly free of vegetation, and composed of earthy or sandy matter. Its effects may be seen in such regions as the sage-brush plains of western North America. The roots of the sage-brush hold the soil immediately about them, but between the clumps of brush where there is little other vegetation, the wind has often blown away the soil to such an extent that the base of each shrub stands up several inches, or even a foot or two, above its surroundings. Such mounds are often partly due to the lodgment of dust about the bushes.

¹ Chamberlin; Jour. of Geol., Vol. V, p. 79.

Since dust is carried to a considerable extent in the upper air, its movements and its deposition are little affected by obstacles on the surface of the land, and when it falls it is spread more or less uniformly over the surface where it settles.

Much of the dust transported by the wind is carried out over seas or lakes and falls into them, causing sedimentation over the bottom of the whole ocean, and at the bottoms of all lakes. The



Fig. 54.— Shows the effect of sage-brush or other similar vegetation in holding sand or earth, or in causing its lodgment in dry regions.

amount of dust blown into the sea cannot well be determined, but it is safe to say that, if such determinations were possible, the result, if stated in terms of weight, would be surprisingly great.

Sand

The wind does not commonly lift sand far above the surface of the land, and its movement is therefore interfered with by surface obstacles, more than are the movements of dust. A shrub, a tree, a fence, a building, or even a stone may occasion the lodgment of sand in considerable quantity, though it has little effect on the lodgment of dust. If the obstacle which occasions the lodgment of sand presents a surface which the wind cannot penetrate, such as a wall, sand is dropped abundantly on its wind-

ward side as well as on its leeward side (Fig. 55); but if it be penetrable, like an open fence, the lodgment takes place chiefly on its leeward side. In cultivated regions, cases are known where,



Fig. 55.— Diagram to illustrate the effect of an obstacle on the transportation and deposition of sand. The direction of the wind is indicated by the upper arrow. The lower arrows represent the direction of eddies in the air occasioned by the obstruction. If the surface in which the obstacle was set was originally flat (dotted line), the sand would tend to be piled up on either side at a little distance from it, but more to leeward. At the same time, a depression would be hollowed out near the obstacle itself (full line). (After Cornish.)

in a few weeks of dry weather, sand has been drifted into lanes in the lee of hedges to the depth of two or three feet, making it difficult for vehicles to pass.

Dunes. In contrast with dust deposited from the atmosphere, wind-blown sand is often aggregated into mounds and ridges called *dunes*. Dunes sometimes reach heights of 200 or 300 feet, but much more commonly they are no more than 10 or 20 feet in height. The shape of dunes depends, among other things, on the extent and form of the area furnishing the sand, the strength and direction of the wind, and the shape of the obstacles which occasion the lodgment.

The shapes of the cross-sections of dunes are influenced by the strength and constancy of the winds. With constant winds and

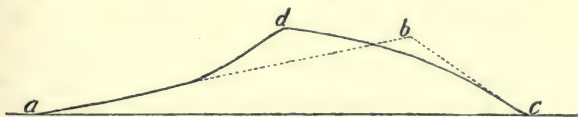


Fig. 56.— Section of a dune showing, by the dotted line, the steep leeward (*bc*) and gentler windward (*ab*) slope. By reversal of the wind, the cross-section may be altered to the form shown by the line *adc*. (Cornish.)

abundant drifting sand, dunes are steep on the lee side (*bc*, Fig. 56), where the angle of slope is the angle of rest for the sand. It rarely exceeds 25° . Under the same conditions, the windward slope is

relatively gentle (*ab*, Fig. 56). If the winds are variable so that the windward slope of one period becomes the leeward slope of another, and vice versa, this form is not preserved. Thus, by reversal of the wind, the section *abc*, Fig. 56, may be changed to *adc*. Where the winds erode (scour) more than they deposit, other profiles are developed. The erosion profiles may be very



Fig. 57.—Dunes at Longport, coast of New Jersey, showing the irregular forms developed by winds which erode.

irregular if the dunes are partially covered with vegetation, as shown in Fig. 57.

The topographic map. Since dunes as well as other topographic features are conveniently represented on contour maps, and since such maps will be used frequently in the following pages, a general explanation of them is here introduced.

“The features represented on the topographic map are of three distinct kinds: (1) inequalities of surface, called *relief*, as plains, plateaus, valleys, hills, and mountains; (2) distribution of water, called *drainage*, as streams, lakes, and swamps; (3) the works of man, called *culture*, as roads, railroads, boundaries, villages, and cities.

“**Relief.** All elevations are measured from mean sea-level. The heights of many points are accurately determined, and those which are most important are given on the map in figures. It is desirable, however, to give the elevation of all parts of the area mapped, to delineate the horizontal outline, or contour, of all slopes, and to indicate their grade or degree of steepness. This is done by lines connecting points of equal elevation above mean sea-level, the lines being drawn at regular vertical intervals. These lines are called *contours*,

and the uniform vertical space between each two contours is called the *contour interval*. On the maps of the United States Geological Survey the contours and elevations are printed in brown (see Pl. I).

"The manner in which contours express elevation, form, and grade is shown in the following sketch and corresponding contour map, Fig. 58.

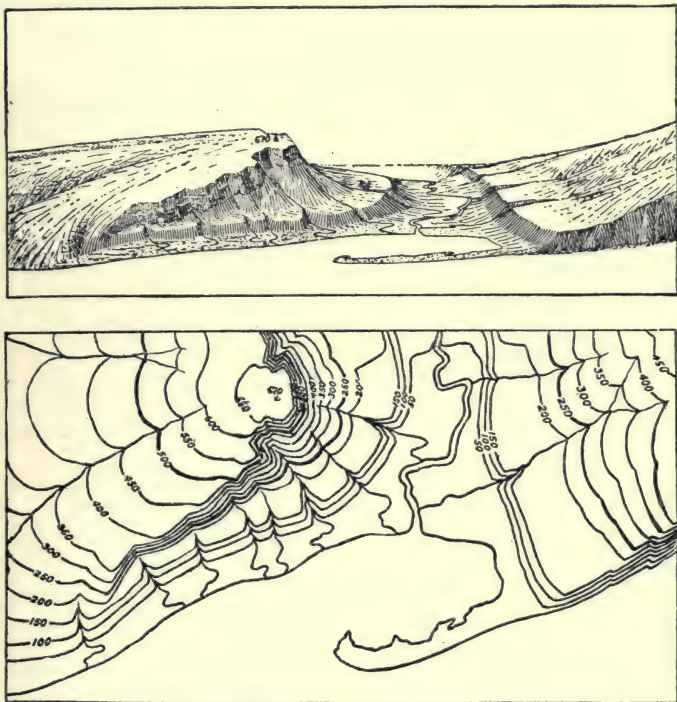


Fig. 58.—Sketch and map of the same area, to illustrate the representation of topography by means of contour lines. (U. S. Geol. Surv.)

"The sketch represents a river valley between two hills. In the foreground is the sea, with a bay which is partly closed by a hooked sand-bar. On each side of the valley is a terrace. From the terrace on the right a hill rises gradually, while from that on the left the ground ascends steeply in a precipice. Contrasted with this precipice is the gentle descent of the slope at the left. In the map each of these features is indicated, directly beneath its position in the sketch, by contours. The following explanation may make clearer the manner in which contours delineate elevation, form, and grade:

"1. A contour indicates approximately a certain height above sea-level. In this illustration the contour interval is 50 feet; therefore the contours are drawn at 50, 100, 150, 200 feet, and so on, above sea-level. Along the contour at 250 feet lie all points of the surface 250 feet above sea; and similarly all elevations above the lower and below the higher contour. Thus the contour at 150 feet falls just below the edge of the terrace, while that at 200 feet lies above the terrace; therefore all points on the terrace are shown to be more than 150 but less than 200 feet above sea. The summit of the higher hill is stated to be 670 feet above sea; accordingly the contour at 650 feet surrounds it. In this illustration nearly all the contours are numbered. Where this is not possible, certain contours — say every fifth one — are accentuated and numbered; the heights of others may then be ascertained by counting up or down from a numbered contour.

"2. Contours define the forms of slopes. Since contours are continuous horizontal lines conforming to the surface of the ground, they wind smoothly about smooth surfaces, recede into all re-entrant angles of ravines, and project in passing about prominences. The relations of contour curves and angles to forms of the landscape can be traced in the map and sketch.

"3. Contours show the approximate grade of any slope. The vertical space between two contours is the same, whether they lie along a cliff or on a gentle slope; but to rise a given height on a gentle slope one must go farther along the surface than on a steep slope, and therefore contours are far apart on gentle slopes and near together on steep ones.

"For a flat or gently undulating country a small contour interval is used; for a steep or mountainous country a large interval is necessary. The smallest interval used on the atlas sheets of the Geological Survey is 5 feet. This is used for regions like the Mississippi delta and the Dismal Swamp. In mapping great mountain masses, like those in Colorado, the interval may be 250 feet. For intermediate relief contour intervals of 10, 20, 25, 50, and 100 feet are used.

"**Drainage.** Watercourses are indicated by blue lines. If the streams flow the year round the line is drawn unbroken, but if the channel is dry a part of the year the line is broken or dotted. Where a stream sinks and reappears at the surface, the supposed underground course is shown by a broken blue line. Lakes, marshes, and other bodies of water are also shown in blue, by appropriate conventional signs.

"**Culture.** The works of man, such as roads, railroads, and towns, together with boundaries of townships, counties, and states, and artificial details, are printed in black."¹

Topography of dune areas. From what has been said, it is clear that the topography of dune regions may vary widely, but

¹ From folio preface, U. S. Geol. Surv.

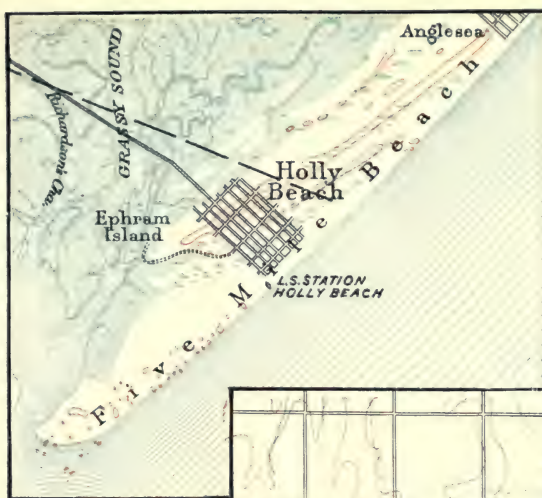


FIG. 1.—Dunes on coast of New Jersey. Scale, about 1 mile per inch. (Cape May Sheet, U. S. Geol. Surv.)

FIG. 2.—Dunes along Arkansas River in Kansas. Scale, about 2 miles per inch. (Larned Sheet, U. S. Geol. Surv.)

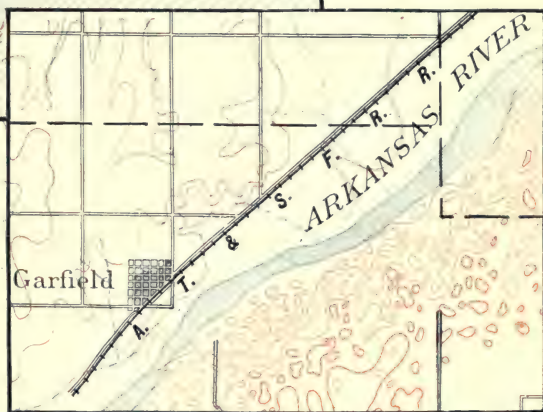


FIG. 3.—Dunes in plains of Nebraska. Scale, about 2 miles per inch. (Camp Clarke Sheet, U. S. Geol. Surv.)

it is always distinctive. Where the dunes take the form of ridges (Fig. 1, Pl. I), the ridges are often of essentially uniform height and width for considerable distances. If there are parallel ridges, they are often separated by trough-like depressions. Where dunes assume the form of hillocks (Figs. 2 and 3, Pl. I), rather than ridges, the topography is even more distinctive. In some regions depressions (basins) are associated with the dune hillocks. Occasionally they are hardly less notable than the dunes themselves.

Explanation of Plate I. In Fig. 1, Plate I (Five Mile Beach, 8 miles northeast of Cape May, N. J.), the contour interval is 10 feet. There is here but one contour line (the 10-foot contour), though this appears in several places. Since this line connects places 10 feet above sea-level, all places between it and the sea (or marsh) are less than 10 feet above the water, while all places within the lines have an elevation of more than 10 feet. None of them reaches an elevation of 20 feet, since a 20-foot contour does not appear. It will be seen that some of the elevations in Fig. 1 are elongate, while others have the forms of mounds. (From Cape May, N. J., Sheet, U.S. Geol. Surv.)

Fig. 2 shows dune topography along the Arkansas River in Kansas (Larned Sheet), and Fig. 3, dune topography in Nebraska (Camp Clarke Sheet), not in immediate association with a valley or shore. In Fig. 2 the contour interval is 20 feet. All the small hillocks southeast of the river are dunes. Some of them are represented by one contour, and some by two. In Fig. 3, where the contour interval is also 20 feet, there are, besides the numerous hillocks, several depressions (basins). These are represented by hachures inside the contour lines. In some cases there are intermittent lakes (blue) in the depressions. There are two depression contours (4280 and 4260) within the contour of 4300, near Spring Lake. The bottom of the depression is therefore lower than 4260, but not so low as 4240.

Migration of dunes. By the continual transfer of sand from its windward to its leeward side, a dune may be moved from one place to another, though continuing to be made up, in large part, of the same sand. In their migration, dunes sometimes invade fertile lands, causing so great loss that means are devised for stopping them. The simplest method is to help vegetation to get a foothold in the sand. The effect of the vegetation is to pin the sand down. As a dune ridge along a coast travels inland, another may be formed behind it, and successions of dune ridges are thus sometimes formed.

When dunes migrate into a timbered region, they bury and kill the trees (Fig. 59). In one instance on the coast of Prussia a tall pine forest, covering hundreds of acres, was destroyed during the brief period between 1804 and 1827.¹ At some points in New Jersey orchards have been so far buried within the lifetime of their owners that only the tops of the highest trees are exposed.



Fig. 59.— Lee side of a sand dune, Cape Henry, Va. The dune is advancing on a forest and burying the trees. (Hitchcock.)

Trees and other objects once buried may be again discovered by farther migration of the sand (Fig. 60).²

Distribution of dunes. Dunes are likely to be developed wherever dry sand is exposed to the wind. They are especially characteristic of the dry sandy shores of lakes and seas, of sandy valleys, and of arid sandy plains.

Along coasts, dunes are likely to be extensively developed only where the prevailing winds are on shore. Thus about Lake Michigan, where the prevailing winds are from the west, dunes are abundant and large on the east shore, and but few and small on the west. Along valleys, dunes are usually on the side toward which

¹ Merrill. *Rocks, Rock Weathering, and Soils*, p. 295.

² Cowles. *The Ecological Relations of the Vegetation of the Sand Dunes of Lake Michigan*. *Botanical Gazette*, Vol. XXVII, 1899. An excellent study of the relations of sand dunes and vegetation.

the prevailing winds blow. Dunes may be formed in the valley bottoms, but the sand is often blown up out of the valley, and lodged on the bluffs above.

Dunes probably reach their greatest development in the Sahara, where some of them take the form of hillocks, and some the form of ridges. They are also conspicuous in other arid, sandy



Fig. 60.—A resurrected forest. After burying and killing the forest, the sand was blown away, exposing the dead trees. (Myers.)

tracts, as in some parts of western Kansas and Nebraska, and in parts of Wyoming.

Eolian sand is not always built up into dunes. It is sometimes spread somewhat evenly over the surface where it lodges. Eolian sand is probably much more widespread than dunes are.

Wind-ripples. The surface of the dry sand over which the wind has blown for a few hours is likely to be marked with ripples (Fig. 61). While the ripples are, as a rule, but a fraction of an inch high, they throw much light on the origin of the great dune ridges. If the ripples be watched closely during the progress of a wind-storm, they are found to shift their position gradually. Sand is blown up the gentler windward slope to the crest of the ridge, and falls down on the other side. Wear on the windward side may be about equal to deposition on the leeward, and the result is the

orderly progression of the ripples in the direction in which the wind is blowing, just as in the case of dune ridges.

Abrasion by the wind. While the effect of the wind on sandy and dusty surfaces is considerable, its effect on solid rock is relatively slight and accomplished by the impact of the sand and dust it carries. Rock worn in this way acquires a surface peculiar to the agency accomplishing the work. If the rock is made up of laminæ which are of unequal hardness, the blown sand digs out



Fig. 61.— A ripple-marked sand dune in a western valley. (U. S. Geol. Surv.)

the softer ones, leaving the harder ones projecting as ridges between them. Adjacent masses of harder and softer rock of whatever thickness are similarly affected. The sculpturing thus effected on projecting masses of rock is often picturesque and striking (Figs. 62, 63), and is most common in arid regions.

Effect of wind on plants. Another effect of strong winds is seen in the uprooting of trees. The uprooting disturbs the surface in such a way as to make loose earth more readily accessible to wind and water. The uprooting of trees on steep slopes often causes the descent of considerable quantities of loose rock and soil.

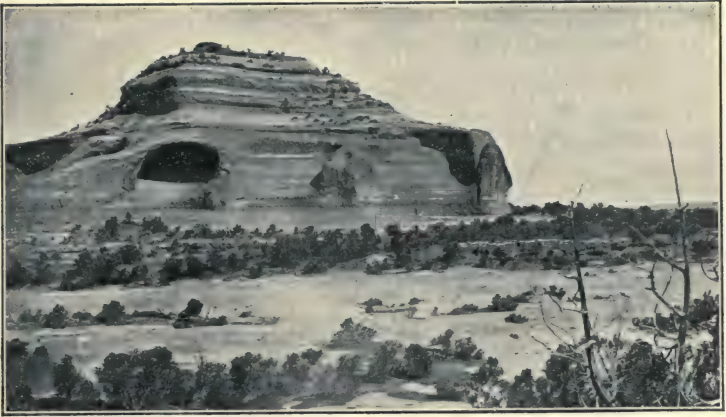


Fig. 62.— Wind erosion. Cave rocks near Sierra La Sal, in Dry Valley, Utah. (Cross, U. S. Geol. Surv.)



Fig. 63.— Wind erosion. Casa Colorado, Dry Valley, Utah, between Abajo and La Sal Mountains. La Plata (Jurassic) sandstone. (Cross, U. S. Geol. Surv.)

Again, organisms of various sorts (certain types of seeds, germs, etc.), as well as dust and sand, are extensively transported by the wind.

Indirect effects of the wind. Other dynamic processes are called into being or stimulated by the atmosphere. Winds generate both waves and currents, and both are effective agents in geological work. The results of their activities are discussed elsewhere.

THE CHEMICAL WORK OF THE ATMOSPHERE

The chemical work of the atmosphere (including solution and precipitation from solution) is principally accomplished in connection with water, a dry atmosphere having relatively little direct chemical effect on rocks or soils. The important chemical changes wrought by the atmosphere are *oxidation*, *carbonation*, and *hydration*. The nature and the results of these processes have already been noted in connection with the decay of rocks (p. 32). A few other effects of the atmosphere may be noted.

Precipitation from solution. The water in the soil is constantly evaporating. Such substances as it contains in solution are deposited where the water evaporates, and where evaporation is long continued without re-solution of the substances deposited, the surface becomes coated with an efflorescence of mineral matter. An example is found in the alkali plains of certain areas in the western part of the United States. Since the alkaline efflorescence is the result of evaporation, it is connected with the atmosphere, but the material of the efflorescence was brought to its present position by water. Other substances deposited when the water which held them in solution is evaporated, coat the pebbles and stones of arid plains in many places. Gravel is thus cemented into conglomerate not infrequently.

Conditions favorable for chemical changes. Conditions are not everywhere equally favorable for the chemical work of the atmosphere. In general, high temperatures facilitate chemical action, and, other things being equal, rocks are more readily decomposed by the chemical action of the atmosphere in warm than in cold regions. Chemical activity is probably greater where the

climate is continuously warm than where there are great changes of temperature. Changes of temperature, on the other hand, tend to disrupt rock, and thus increase the amount of surface exposed to chemical change. Since nearly all the chemical changes worked by the atmosphere on the rocks are increased by the presence of moisture, the chemical activity of the atmosphere is greater in moist than in dry regions.

Though the chemical changes effected by the air are slow, their importance in the course of the earth's long history must have been very great. The amount of rock which has been thus disintegrated probably far exceeds all that is now above the sea (Chapter VII).

THE ATMOSPHERE AS A CONDITIONING AGENCY

The most obvious mechanical work of the atmosphere is effected by the wind, but mechanical results conditioned by the atmosphere are also effected when the air is still.

Temperature effects. The disrupting effects of changes of temperature have been described briefly (p. 31) and illustrated (Figs. 13 and 14). Several conditions determine the efficiency of this process. The greater and the more sudden the change of temperature, the greater the breaking, the suddenness of the change being more important than its amount. It follows that great daily, rather than great annual, changes of temperature¹ favor rock-breaking. A partial exception to this generalization should be noted. If the pores and cracks are *full* of moisture, a change of temperature from 45° to 35° (Fahr.) might be far less effective in breaking the rock than a change from 35° to 25° in the same time, for in the latter case the sudden and very considerable expansion (about one-tenth) which water undergoes on freezing is brought into play. This may be called the *wedge-work of ice*.

The daily range of temperature is influenced especially by (1) latitude, (2) altitude, and (3) humidity. (1) If other things were equal, the greatest daily ranges of temperature would be in low

¹ It should be noted that it is the change of temperature of the rock surface, not the change of temperature of the air above it, which is to be considered.

latitudes. (2) High altitudes favor great daily ranges of temperature, *so far as the rock surface is concerned*, for though the rock becomes heated during the sunny day, the thinness and dryness of the atmosphere allow the heat to radiate rapidly at night. Here, too, the daily range of temperature is likely to bring the wedge-work of ice into play. Since the south side of a mountain (in the



Fig. 64.—Erosional forms characteristic of dry regions where erosion by the wind is effective. Fissure Canyon, on the north slopes of the La Sal Mountains, Utah. The rock is Permian. (Cross, U. S. Geol. Surv.)

northern hemisphere) is heated more than the north, it is subject to the greater daily range of temperature, and the rock on this side suffers the greater disruption. Similarly, rock surfaces on which the sun shines daily are subject to greater disruption than those much shielded by clouds. (3) The daily range of temperature is also influenced by humidity, a rock surface becoming hotter by day and cooler by night beneath a dry atmosphere than beneath a moist one. Aridity, therefore, favors the disruption of rock by

changing temperatures. The color of rock, its texture, and its composition also influence its range of daily temperature, by influencing absorption and conduction. In general, crystalline rocks are more subject to disruption by this means than sedimentary rocks, partly because they are more compact, and partly



Fig. 65.—A mountain top, showing a common condition of the rock in the mountain peaks.

because they are made up of aggregates of crystals of different minerals which, under changes of temperature, expand and contract at different rates, while the common sedimentary rocks are made up largely of numerous particles of one mineral.

The disrupting effects of changes of temperature are slight or nil where the solid rock is protected by soil, clay, sand, gravel, snow, or other incoherent material. If the constituent parts of

the loose material are coarse, like boulders, their surfaces are affected like those of larger bodies of rock.

In view of these considerations, the breaking of rock by changes of temperature should be greatest on the bare slopes of isolated elevations of crystalline rock, and where the atmosphere is relatively free from moisture. All these conditions are not often found in one place, but the disrupting effects of changing temperatures are best seen where several of them are associated.



Fig. 66.— Serrate mountain peaks with abundant talus. Cascade Mountains, Washington.

The importance of this method of rock-breaking is rarely appreciated except by those familiar with high and dry regions. Mountain climbers know that most high peaks are covered with broken rock to such an extent as to make their ascent dangerous to the uninitiated. High serrate peaks, especially of crystalline rock, are, as a rule, literally crumbling to pieces (Fig. 65). The piles of talus which lie at the bases of steep mountain slopes (Fig. 66) are often hundreds of feet in height, and their materials are often in large part the result of the process here under discussion. Masses

of rock, scores and even hundreds of pounds in weight,¹ are sometimes detached in this way, and started on their downward course, but small pieces of rock are of course much more commonly broken off than large ones.

The sharp peaks which mark the summits of most high mountain ranges (Fig. 65) are largely developed by the process here outlined. The altitude at which the serrate topography appears varies with the latitude, being as a rule, higher in low latitudes and lower in high. But even in the same latitude it varies notably with the isolation of the mountains and the humidity of the climate. Thus within the United States the sharply serrate summits (Fig. 67) appear in Washington and Oregon at altitudes of 6,000 to 10,000

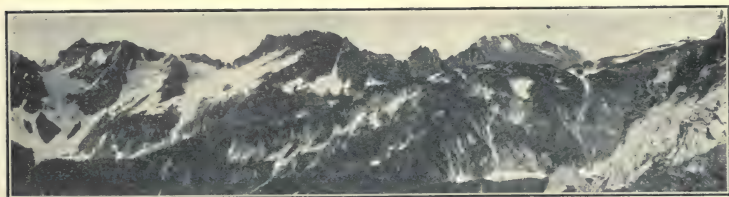


Fig. 67.—Serrate mountain tops. Cascade Range, Washington. (Photo. by Tolman.)

feet, while in the isolated Wichita range of Oklahoma, much farther south in a drier climate, the same sort of topography is developed at altitudes of 2,500 to 3,000 feet.

Even in low latitudes and moist climates the effects of temperature changes are often seen. For example, thin beds of limestone at the bottoms of quarries are sometimes so expanded by the heat of the sun as to arch up and break.

The disruption of rock by changes of temperature is one phase of weathering. It tends to the formation of a mantle of rock waste, which, were it not removed, would soon completely cover the solid rock beneath and protect it from further disruption by heating and cooling; but the loose material thus produced be-

¹ Livingstone has reported that the temperature of rock surfaces in Africa sometimes reaches 137° Fahr. during the day, and cools sufficiently at night to split off blocks of 200 lbs. weight.

comes an easy prey to running water, so that the work of the atmosphere prepares the way for that of other eroding agencies.

Evaporation and precipitation. Perhaps the most important work of the atmosphere as a geologic agent, lies in its relation to the evaporation, circulation, and distribution of water. Atmospheric temperature is the primary factor governing evaporation, an important factor in the circulation of the vapor after it is formed, and controls its condensation and precipitation.

It is impossible to separate sharply the geologic work of the water of the atmosphere from that of other waters; but so long as moisture is in the atmosphere (including the time of its precipitation) its effects are best considered in connection with the atmosphere.

The mechanical work of the rain. In falling, the rain washes the atmosphere, taking from it much of the dust, spores, etc., which the winds have lifted from the surface of the dry land. Not only this, but in passing through the atmosphere, the water dissolves some of its gases, so that when the rain reaches the land, it is no longer pure, and some of the gases it has taken up in its descent enable it to dissolve various mineral matters on which pure water has little effect.

As it falls on the surface of the land, the rain produces various effects of a mechanical nature. In the first place, it leaves on the surface the solid matter taken from the air. Clayey soils are baked under the influence of the sun, and when in this condition are softened by the rain, and more easily removed by running water. Under the influence of the expansion and contraction caused by wetting and drying, the soils and earths on slopes creep slowly downward. When rain falls on dry sand or dust the cohesion is at once increased, and shifting by the wind is temporarily stopped.

After the water has fallen from the air, its further work cannot be looked upon as a part of the work of the atmosphere; but the proper conception of the geological work of the atmosphere must recognize that the waters of the land have come through the atmosphere.

Effects of electricity. Another dynamic effect conditioned by the atmosphere is that produced by lightning. In the aggre-

gate, this result is inconsequential; yet instances are known where large bodies of rock have been fractured by a stroke of lightning, and masses many tons in weight have sometimes been moved appreciable distances. Incipient fusion in very limited spots is also known to have been induced by lightning. Thus where it strikes sand it often fuses the sand for a short distance, and, on cooling, the partially fused material is consolidated, forming a little tube or irregular rod (a *fulgurite*) of partially glassy matter. Fulgurites are usually only a few inches in length, and more commonly than otherwise a fraction of an inch in diameter.

SUMMARY

On the whole, the tendency of the work of the atmosphere and of the work which is controlled by it, is to degrade the land, and to loosen materials of the surface so that they may be readily moved to lower levels by other agencies. The most important phase of the degradational work of the atmosphere is *weathering*, or the preparation of material for removal by other and more powerful agents of degradation. As we shall see, however, the atmosphere is not the only agent concerned in weathering (see p. 140).

The wind has doubtless been an important agent in the transportation of dust and sand, wherever and whenever there was dry land, ever since an atmosphere has existed. If it has been as effective as now through all the untold millions of years since there have been land and atmosphere, the total amount of work which it must have done is past calculation. Wind-deposited sand, now cemented into solid rock, has been identified, even in very ancient formations.

Laboratory work. The study of topographic and geologic maps, photographs, etc., illustrating wind work may well be taken up in connection with this chapter. Numerous sheets of the topographic maps published by the United States Geological Survey afford illustrations of dunes; so also do a few of the folios. Plates XVI to XXII of Professional Paper 60 of the U. S. Geological Survey afford good illustrations of wind work. A fuller list of topographic maps available for this purpose is to be found on p. 78 of the junior author's *Physiography* (Advanced Course).

CHAPTER IV

LAND WATERS — STREAMS

The average amount of precipitation on the land is estimated at about 40 inches per year. A part of this water sinks beneath the surface, a part forms pools or lakes on the surface, a part runs off over the surface at once, and a part of it is evaporated. The proportion of the rainfall in any given place which follows each of these courses depends on several conditions, among which are (1) the topography of the surface, (2) the rate of rainfall (or the rate at which the snow melts), (3) the porosity of the soil or rock, (4) the amount of water which the soil contains when the rain falls or the snow melts, (5) the amount of vegetation on the surface, and (6) the dryness of the atmosphere. The steeper the slopes, the more rapid the rainfall, the less porous the soil, the wetter it is, and the less the vegetation, the more water will run off without sinking beneath the surface.

The water which sinks into the ground becomes *ground-water*, while that which flows off over the surface without sinking is the *immediate run-off*. Much of the ground-water ultimately reaches the surface again, and some of it joins the immediate run-off in the streams. All the water which the streams carry, whether it has been beneath the surface or not, is the *run-off*. Whether the water which falls as rain stands on the land in lakes, runs off as rivers, or sinks beneath the surface, it is more or less active, and the results of its activity are seen on every hand.

THE WORK OF RUNNING WATER

Rivers are estimated to carry about 6,500 cubic miles of water to the ocean annually. The average height of land is nearly half a mile, and the waters which flow from the land to the sea therefore

fall, on the average, nearly half a mile in their flow. Their energy is therefore great, and they are the great carriers of sediment from

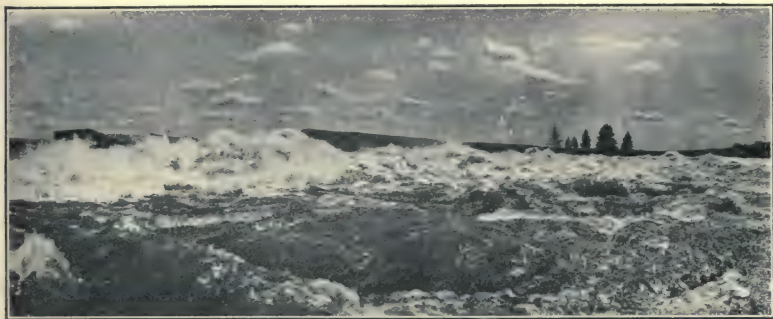


Fig. 68.— Spokane River, 4 miles above Spokane, during flood. (Photo. by Tolman.)

land to sea. The sediment which they carry is composed largely of decayed rock, but undecayed rock is sometimes worn away, especially where streams are very swift.



Fig 69.— Scene in the freight-yards of Kansas City after the flood of 1903. (U. S. Weather Bureau.)

Though the flow of some streams is so gentle that they do not appear to work great changes in their valleys, others wear away their banks so rapidly that the changes they produce may be seen

from year to year, or, sometimes, when the stream is in flood, from day to day. The force of streams at such times is often disastrous (Fig. 68). Occasionally they sweep away dams, bridges, and even buildings on their banks. The strong rods and beams of the bridges, and the steel rails of railways are bent almost as if they were twigs by the force of the occasional torrent which follows an exceptional rain, such as a cloudburst (Fig. 69).

The source of river water is the rain and snow which fall from the atmosphere. This may be inferred from various familiar



Fig. 70.

Fig. 70.— Map showing the many streams of a humid region. Central Kentucky. The area is about 225 square miles.



Fig. 71.

Fig. 71.— Map showing the few streams of an arid region. Northern Arizona. The area is as great as that shown in Fig. 70.

phenomena. Thus (1) streams are more numerous in regions where the rainfall is abundant than in those where it is scarce (Figs. 70-71); (2) multitudes of small streams spring into being with each heavy fall of rain and with each period of rapidly melting snow; (3) streams are notably swollen after rains, and most after heavy ones; and (4) many small streams which flow during wet weather dry up in times of drought, while others shrink. It is true that lakes, glaciers, and springs feed the rivers, but the lakes, glaciers, and springs derive their supply of water from precipitation.

If the slope of a surface were perfectly even, the immediate run-off at any given time would flow in a sheet. There are slopes so smooth that water runs off them in this way; but on most slopes, even those which appear to be regular, there are small unevennesses, so that, although the run-off may start as a sheet, it is soon concentrated into rills and streamlets which follow the depressions. The smallest streamlets unite to form larger ones, and the little rills, after many unions with one another, reach valleys which



Fig. 72.— A gully developed by a single shower. (Blackwelder.)

have *permanent streams*. These may be small (creeks or brooks) or large (rivers). Streams which flow but part of the time, as after a rain-storm, during wet weather, or during but a part of the year, are *temporary* or *intermittent streams*.

Every permanent stream and many temporary ones flow in depressions called *valleys*. Valleys are therefore about as numerous as streams. The very small depressions in which water runs only after showers are called *gullies* if they are very small (Fig. 72), or *ravines* if somewhat larger. Gullies and ravines are but small valleys, and just as the tiny streamlets unite to form creeks and these to form rivers, so the little gullies in which the smallest temporary

streams flow, generally unite to form wider and deeper ones (Fig. 73). These, in turn, join one another and become ravines, which are but larger depressions of the same sort, and ravines lead to valleys, just as gullies lead to ravines. Valleys, like streams, usually end at the ocean or a lake; but in some cases, especially in arid regions, they end on dry land.

There is as a rule, some relation between the size of a valley and the stream which follows it, though this relation is not one which



Fig. 73.— Slope with numerous gullies, the smaller ones joining the larger ones. Scott's Bluff, Neb. (U. S. Geol. Surv.)

can be stated in mathematical terms. The large stream and the large valley go together so often, however, that the combination cannot be accidental.

EROSIVE WORK OF RUNNING WATER

Wherever water flows over the land, it wears the surface on which it flows, and the faster it flows, the greater its power of

erosion. The rate of flow is determined by several conditions, especially (1) the gradient (slope), (2) the amount and especially the depth of the water, and (3) the amount of sediment (load) it is carrying. The higher the gradient, the deeper the water, and the less the load it is carrying, the faster it flows. If it flows off in a sheet, as on a smooth surface, the depth of the water is slight, and the flow is not very swift (unless the slope is very steep), and the wear is correspondingly slight. Such wear is sometimes called *sheet erosion*.

Beginning of a valley. 1. If the slope of the surface is not uniform, the effect is very different. If there is, for example, a slight depression near the base of the slope (Fig. 75), more of the descending

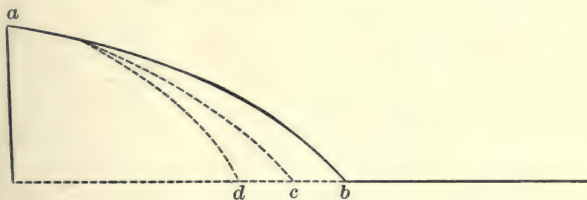


Fig. 74.—Figure to illustrate the steepening of a slope by general sheet wash; ab would be reduced to ac and to ad successively, if the débris washed down were not deposited at the base. The deposition of débris at the base would modify the lower part of the slope.

water flows through it than over other parts of the surface, and the greater volume of water following the depression would give it greater velocity. Greater velocity would cause greater erosion, and greater erosion would deepen the depression. The immediate result would be a *gully* or *wash* (Fig. 72). So soon as the gully is started, it tends to concentrate drainage in itself still more, and it is thereby enlarged. The water which enters it from the sides widens it; that which enters at its head lengthens it, by causing its upper end to advance up the slope; and all which flows through it, deepens it. The enlarged gully will gather more water to itself, and, as before, increased volume means increased velocity, and increased velocity, increased erosion. As the gully grows, therefore, its increased size becomes the occasion of still further growth. Continued growth transforms the gully into a ravine, though there

is no distinct line of demarkation between the two. But growth does not stop with ravine-hood. Water from every shower gathers in the ravine, and, flowing through it, increases its length, width, and depth, until it becomes a valley.

It was assumed in the preceding paragraphs that the single depression in the slope was meridional and low on the slope; but almost any sort of depression in almost any position would bring about a similar result, since it would lead to concentration of the run-off. Had the original surface been marked by a ridge instead of a depression, the effect on valley development would have been much the same, for a ridge, like a depression, would cause the



Fig. 75.—Diagram showing a slight meridional depression in the surface of an otherwise even-sloped island.

concentration of the run-off along certain lines, and therefore lead to the development of valleys.

Under the conditions represented in Fig. 75 the lengthening of the drainage depression is effected chiefly at its upper end, the head of the valley working its way farther and farther back into the land. This method of lengthening is known as *head erosion*. But the lengthening of the valley is not always wholly by head erosion. The gully begins normally where concentration of run-off begins, and if this is not at sea-level, the gully may be lengthening at both ends at the same time. This would have been the case, for example, had the original depression of Fig. 75 been half-way up the slope of the island. Valleys developed under the control of surface slope are *consequent valleys*, and their streams are *consequent streams*.

2. If the surface material of a slope is of unequal resistance, the water flowing over it may develop irregularities of slope, even if the slope was uniform at the outset. Thus if the material of a certain part of the slope is less resistant than that elsewhere, the run-off will erode most where the material is least resistant. The

depression thus started will be a cause of its own growth, and, as before, the gully might develop into a valley.

In the presence of sufficient rainfall, therefore, either heterogeneity of slope or of material will occasion the development of valleys. If lack of uniformity appears at but few points, there will be but few valleys; if at many points, the number of valleys will be large. Since it is unlikely that any great area of land ever had perfectly homogeneous material and absolutely uniform slopes, every considerable land area, affected for any considerable length of time by abundant rain, has had valleys developed in it; and the heterogeneity of material and slope is usually such that valleys are developed at short intervals.

The permanent stream. It appears from the foregoing discussion that a valley may be developed by the run-off of successive showers. If supplied from this source only, surface streams would cease to flow soon after the rain ceased to fall, and a valley might attain considerable size without possessing a permanent stream. How does the valley developed by the run-off of successive showers come to have a permanent stream? The answer to this question involves a brief consideration of that part of the rainfall which sinks beneath the surface.

If wells are sunk in a flat region of uniform structure and composition, the water in them is generally found to stand at a nearly common level. If a hole 60 feet deep fills with water up to a point 20 feet below the surface, it is because the material in which the well is sunk is full of water up to that level. When the well is dug, the water leaks into it, filling the hole up to the level to which the rock (or subsoil) is itself full. This level, below which the rock and subsoil (down to unknown depths) are full of water, is known as the *ground-water level*, or better, the *ground-water surface*, or *water-table*.

The ground-water surface fluctuates. It rises during wet weather, because more water sinks then; but several processes conspire to bring it down again. (1) Where there is growing vegetation, its roots draw up water from beneath; (2) evaporation goes on independently of vegetation; (3) the water is drawn out through wells, mines, etc., and runs out as springs; and (4) it flows

underground from places where the water-table is higher to those where it is lower. In these and other minor ways the ground-water surface is depressed.

A well sunk to such a level as to be supplied with abundant water in a wet season may go dry during a period of drought because the ground-water level is depressed below its bottom.

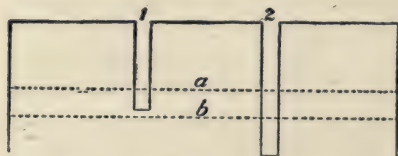


Fig. 76.— Diagram illustrating the fluctuation of the ground-water surface; *a* = wet-weather ground-water level; *b* = ground-water level during drought. Well No. 1 will contain water during the wet season, but will go dry in times of drought. Well No. 2 will be permanent.

Thus either well shown in Fig. 76 will have water during a wet season when the water-level is at *a*; but well No. 1 will go dry when the water surface is depressed to *b*.

These principles are as applicable to valleys as to wells. When a valley has been deepened until its bottom is below the ground-water surface, water

seeps or flows into it from the sides. The valley is then no longer dependent on the run-off of showers for a stream. When the bottom of a valley is below the ground-water level of a wet season, without being below that of a dry one, it will have an intermittent stream. If the rainfall of the year were concentrated in a single wet season, the intermittent stream would flow not only during that season, but for so long a time afterward as the ground-water level remained well above the valley bottom. In regions subject to frequent and short periods of precipitation alternating with droughts, the periods of intermittent flow may be many and short. Many valleys are now in the stage of development where their streams are intermittent.

As a valley containing an intermittent stream becomes deeper, the periods when it is dry become shorter, and when it has been sunk below the lowest ground-water level, it will have a permanent stream (3, Fig. 77). Since a valley normally develops headward, its lower and older portion is likely to acquire a permanent stream while its upper and younger part has only an intermittent one. So soon as a valley gets a permanent stream, the process of valley-

enlargement goes on without the interruption to which it was subject when the supply of water was intermittent.

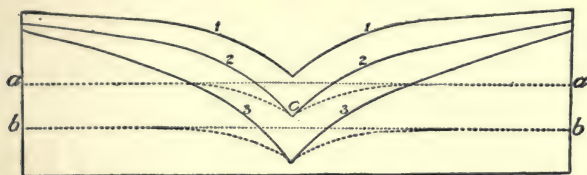


Fig. 77.— Diagram to illustrate the intermittency of streams due to fluctuations of the ground-water level. The water level *aa* would be depressed next the valley 2-2, by the flow of the water into the valley. The profile of the ground-water surface would therefore be *aca* rather than *aa*.

In general a permanent stream at one point in a valley means a continuous stream from that point to the sea or lake which the valley joins; but to this rule there are many exceptions. They are likely to arise where a stream heads in a region of abundant precipitation, and flows thence through an arid tract where the ground-water level is low, and evaporation great. In such cases, evaporation and absorption may dissipate the water gathered above, and the stream disappears (Pl. II).

Other modes of valley development. Valleys are not always developed from gullies in the manner outlined above. The outflow of a lake would develop a valley, but the valley might be in process of excavation all the way from the lake basin to the sea at the same time (Fig. 78). A valley developed in this manner is not simply

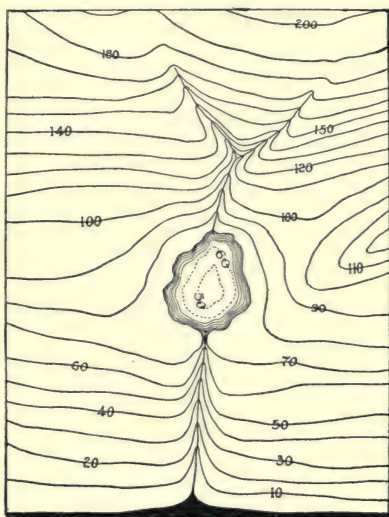


Fig. 78.— Diagram to show how a valley may be developing all the way from a water-filled basin (lake) to the sea at the same time. Small valleys leading to the lake are also developing. The black area = the sea.

a gully grown big by head erosion, and the valley would not precede the stream.

If a narrow coastal plain is limited landward by a steeper slope, valleys might develop as shown in Figs. 79 and 80. Again, in

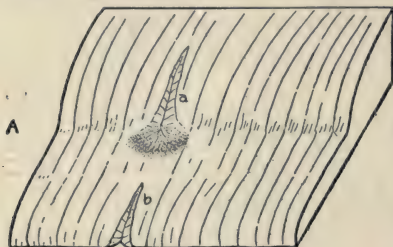


Fig. 79.

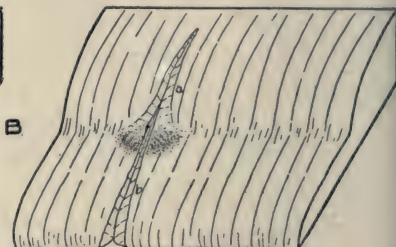


Fig. 80.

Figs. 79 and 80.—Diagram to illustrate one mode of valley lengthening. In Fig. 79 there are two small valleys, *a* and *b*, and the former ends at the base of the steep slope. In Fig. 80, valley *b* is represented as having been lengthened so as to join *a*, and the two have become one.

mountain regions valleys are sometimes formed by the uplift of parallel mountain folds, leaving a depression between (Fig. 81). Drainage will appropriate such a valley so that it becomes in some sense a river valley. But it is not a river valley in the sense in which the term has been used in the preceding pages. It is rather

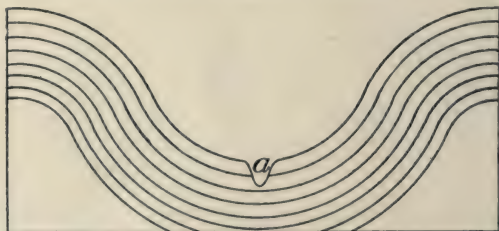
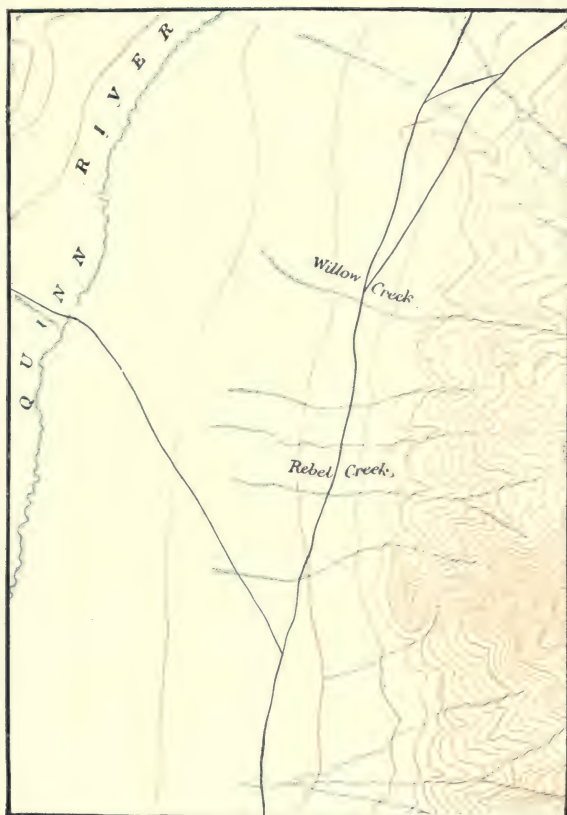


Fig. 81.—Structural valley with a river valley developing in its bottom.

a *structural valley*. A river valley may be developed in its bottom (*a*, Fig. 81) and it may be in process of development throughout the structural valley at the same time.

These illustrations do not exhaust the list of conditions under which valleys develop, but they suffice to show that valleys originate and develop in different ways.

PLATE II



Streams disappearing in the sand, gravel, etc., at the base of mountains in an arid region. Scale, about 4 miles per inch. (Paradise, Nev., Sheet, U. S. Geol. Surv.)

PLATE III



Youthful valleys. Shore of Lake Michigan just north of Chicago. Scale, about 1 mile per inch. (Highwood Sheet, U. S. Geol. Surv.)

Limits of growth. In all cases there are limits in depth, length, and width, beyond which a valley may not grow. A stream flowing to the sea tends to erode its valley to sea-level,¹ but actually reaches the sea-level only at the coast. The lowest level to which running water can wear a land surface is a *base-level*. In length, the valley will grow as long as its head continues to work inland. If but a single valley affected a land area, the limit toward which it would tend would be the length of the land area in the direction of the valley's axis. In general, valleys are limited in length by other valleys. The head of a valley works back until it reaches a point where erosion toward the valley in question is equal to erosion in the opposite direction. Here the divide becomes permanent (Fig. 82.) In width, a valley is increased chiefly by the

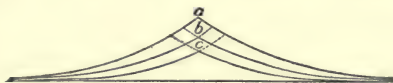


Fig. 82.— Diagram to illustrate the lowering of a divide without shifting it. The crest of the divide is at *a*, *b*, and *c* successively. If the erosion was unequal on the two sides, the divide would be shifted.

side cutting of the stream, by the wash of the rain which falls on its slopes, and by the action of gravity which tends to carry down to the bottom of the slope the material which is loosened above by any process whatsoever. The widening of valleys is limited much as their lengthening is. Adjacent valleys grow wider until the tops of the intervening divides are reduced to lines. Then, if erosion is equal on the two sides, the divide is lowered without shifting, so far as slope wash is concerned.

The development of tributaries. Most considerable valleys have numerous tributaries. So soon as a gully is started, the water flowing into it from either side wears back the slopes. A slight inequality of slope, or a slight variation in the character of the material, is sufficient to make the erosion of the slopes unequal at different points, and unequal erosion in the slopes results in the development of tributary gullies. Tributary gullies develop into ravines and valleys, the same as their mains. Every new

¹ Great rivers, like the Mississippi, cut their *channels* somewhat below sea-level, for miles above their debouchures.

valley facilitates the run-off of the water which falls on the land, and so helps along erosion.

The struggle for existence among valleys and streams. It is not to be inferred that every gully becomes a valley, nor that every small valley becomes a large one. The number of miniature gullies which develop on a slope may be very large (Fig. 73); but the history of many of them is ephemeral. If two adjacent ones are of unequal depth, the widening of the deeper narrows and finally eliminates the divide between them, and the two become one (Fig. 83).

Any good map of the north shore of Lake Superior, or the west shore of Lake Michigan shows a large number of small streams

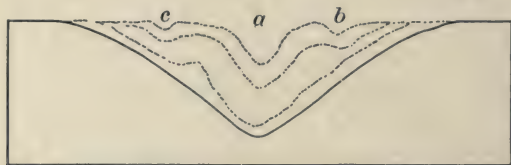


Fig. 83.— Diagram illustrating how one gully takes another as a result of lateral erosion.

and gullies (Pl. III). No equal stretch of coast has a number of large valleys comparable to that of the small ones along such shores. It therefore seems evident that of these many small valleys a few only will attain considerable size.

Some of the young valleys work their heads back into the land faster than others, because of inequalities of slope and material. If valleys develop in ways other than by head erosion, the chances are also against their equal growth. If two streams, such as *a* and *c*, Fig. 84, develop faster than the intermediate stream *b*, it is clear that their tributaries may work back into the territory which at the outset drained into *b*, so as to cut off the supply of water from the latter stream (compare *a'b'c'*, Fig. 85). As a result, the growth of *b* will be checked, and ultimately stopped. Similarly other valleys, such as *f* (Fig. 84), will get the better of their neighbors, and many of the competitors, as *b'*, *d'*, *e'*, and *g'* (Fig. 85), will soon drop out of the race. Between the stronger streams

competition still goes on. If a' and f' (Fig. 85) develop faster than c' , its prospective drainage territory will be pre-empted by its rivals (compare Figs. 85 and 86). Thus as the result of the unequal rate

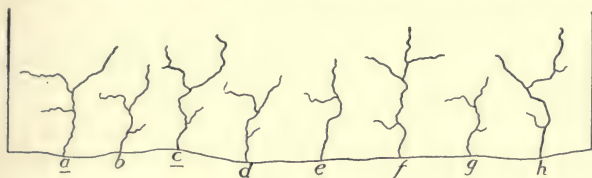


Fig. 84



Fig. 85.

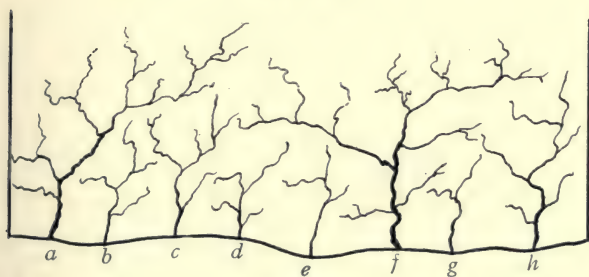


Fig. 86.

Figs. 84, 85, and 86.— Diagrams illustrating successive stages in the struggle for existence among streams.

at which valleys are lengthened, the larger number of those which come into existence are arrested in their development.

Piracy. Streams do not always hold the courses which they establish for themselves in youth. Thus the valley of the Potomac River across the Blue Ridge (Fig. 87) was deepened faster than that of Beaverdam Creek. The head of the young Shenan-

doah River then worked back and tapped Beaverdam Creek, *diverting* its head waters to the Potomac (Fig. 88). The young Shenandoah was a *pirate*, and Beaverdam Creek was *beheaded*. The stream to which waters are diverted is increased in size, and the beheaded stream is correspondingly diminished; or if its total supply of water came in above the point of tapping it would disappear altogether.

An actual case of piracy is shown on Plate IV. North and South Lakes formerly drained westward to the Schoharie Creek,

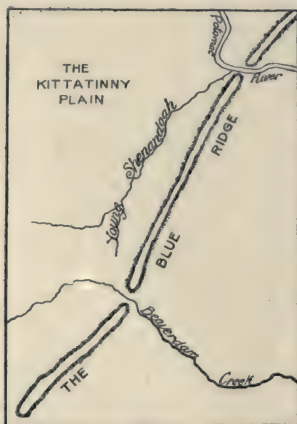


Fig. 87.



Fig. 88.

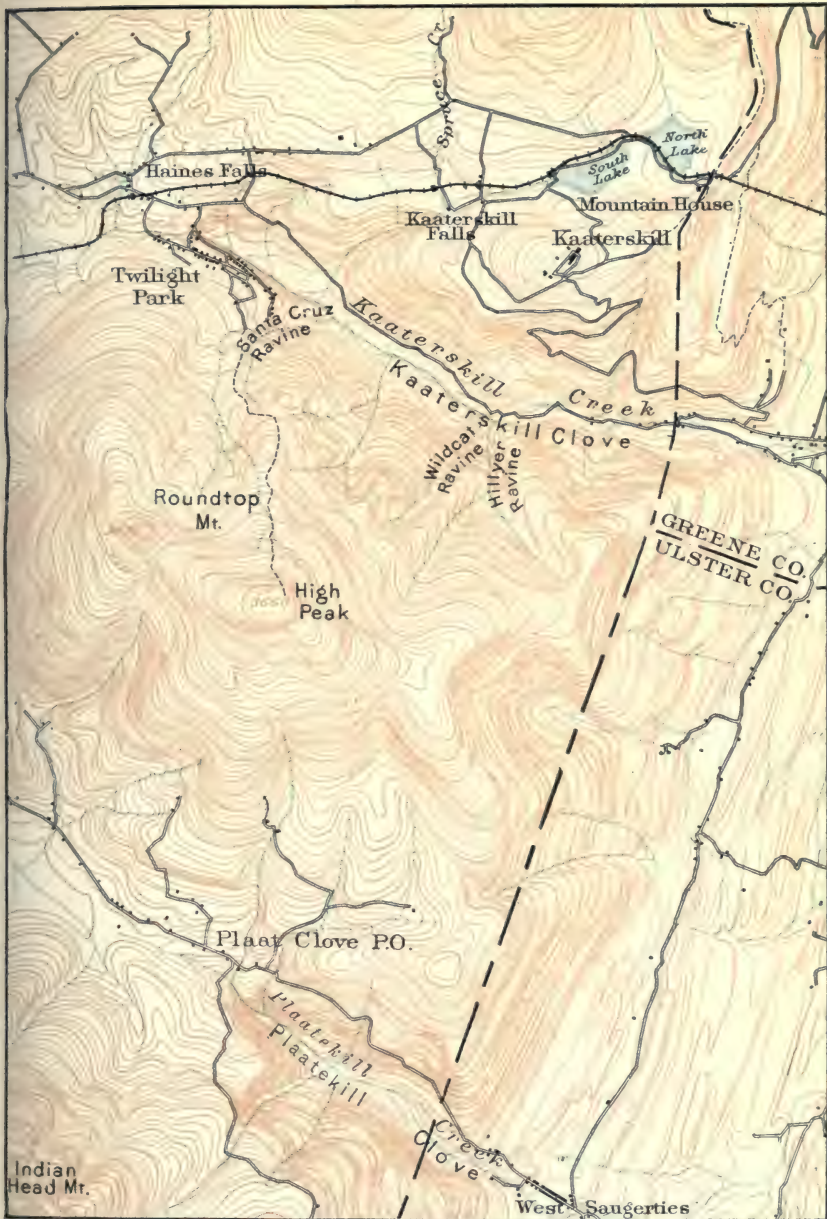
Figs. 87 and 88.— The capture of the head of Beaverdam Creek by the Shenandoah River. Virginia–West Virginia. (After Willis.)

the present head of which is in the extreme northwest corner of the map. The head of Kaaterskill Creek, which had a much higher gradient, worked back and captured the head of the westward-flowing stream, diverting the drainage from North and South Lakes to itself. Schoharie Creek was thus beheaded.

Plaatekill Creek, near the south limit of the map, appears to have beheaded the creek flowing west and northwest, similarly diverting its head waters.

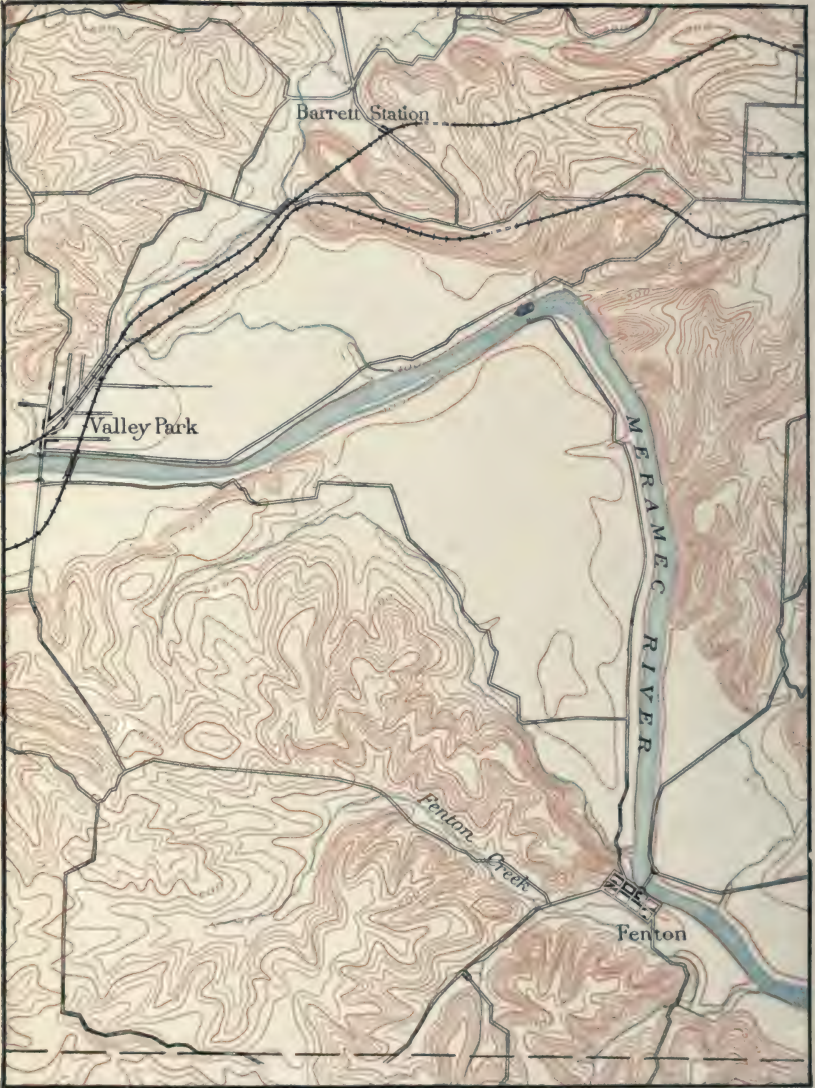
A Cycle of Erosion

From what has preceded it is clear that the topography of a region undergoing erosion will change greatly from time to time.



Map illustrating piracy. The drainage from North Lake and South Lake was once westward to the westward flowing creek southwest of Haines Falls. The head of a tributary of Kaaterskill Creek worked back, capturing, near Kaaterskill Falls, the creek which formerly flowed westward, and diverted it southward to Kaaterskill Creek. Scale, about 1 mile per inch.

PLATE V



A stream widening its valley by lateral planation Scale, about 1 mile per inch. (U. S. Geol. Surv.)

The first effect of erosion by running water is to roughen the surface by cutting out valleys, leaving ridges and hills. The final effect is to make it smooth again by cutting the ridges and hills down to the level of the valley bottoms.

Base-level, peneplain, grade. A base-level of erosion has already been defined; but the mode of its development may now

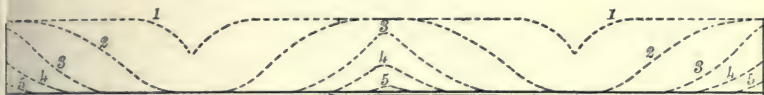


Fig. 89.— Diagram to illustrate the leveling of the surface by valley erosion. The profile represented at the top shows two young valleys, 1 and 1, in an otherwise flat surface. In time these valleys will develop the cross-sections represented by 2 and 2, and later those represented by 3 and 3, 4 and 4, etc. The divide between them may finally reach 5, and the surface is then nearly flat.

be illustrated in the light of the preceding discussion. Suppose a land surface affected by a series of parallel young valleys without tributaries (Fig. 89). Between them there is a series of upland plains or plateaus. The profile of the surface between two adjacent valleys is represented in section by the uppermost line in Fig. 89. As the valleys are widened from 1 and 1 to 2 and 2, the inter-

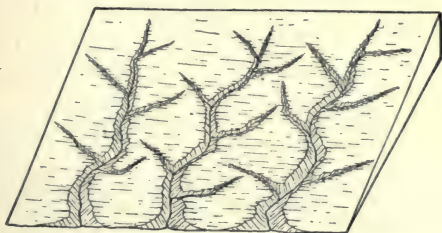


Fig. 90.— Diagram showing tributaries in an early stage of development.

vening upland is correspondingly narrowed. When the valleys have attained the form represented by 3 and 3, the intervening upland has been narrowed to a ridge, and the valley flats have become wide. With continued erosion the ridge will be lowered still more, and in time the surface will approach a plain. In this condition it is known as a *peneplain*. The ridges will be obliterated finally, and a base-leveled plain results.

Tributaries are almost sure to develop along each main valley and their heads work back across the uplands between the main



Fig. 91.— A mountain slope thoroughly cut up by erosion of running water. Looking east from Echo Rock, on Mount Wilson, California. (Ellerman.)

valleys, dissecting them into secondary ridges (Fig. 90). Tributaries will develop on the tributaries, and these tertiary valleys dissect the secondary ridges into ridges of a lower order. This



Fig. 92.— Appalachian mountain topography near Canton, North Carolina. The foreground shows a plateau now well drained. (Keith, U. S. Geol. Surv.)

process of tributary development goes on until drainage lines of the fourth, fifth, sixth, and higher orders are formed (Fig. 93). Since the process of valley development under such circumstances is also the process of ridge dissection, a stage is presently reached

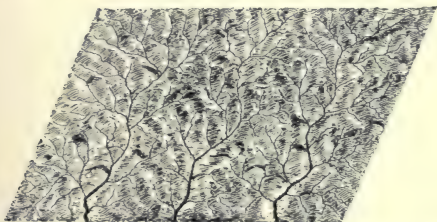


Fig. 93.— Diagrammatic representation of a surface much dissected by the development of numerous tributaries.

where the ridges are cut into such short sections that they cease to be ridges, and becomes hills instead. Even then the processes of erosion do not stop, for rain-water falling on the hills washes the loose material from their surfaces, and starts it on its seaward

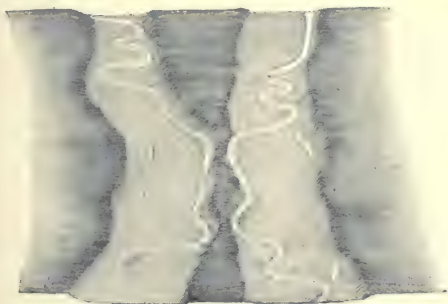


Fig. 94.— Diagram showing streams in adjacent valleys, undercutting the divide between them. They may, in time, destroy the divide by lateral planation.

journey. Thus the “everlasting hills” are lowered, and, given time enough, they will be carried to the sea.

The base-leveled surface is not absolutely flat. The area reduced by each stream will have a slight slope down-stream, and from its sides toward its axis. The low divides between streams

flowing in the same direction may, however, disappear altogether, for when valleys have reached their limits in depth, their streams do not cease to cut laterally. Meandering in their flat-bottomed valleys, they often reach and undercut their divides (Pl. V, and Fig. 94). By *lateral planation*, therefore, the divides between streams may be entirely eaten away. The time involved in the reduction of a land area to base-level is a *cycle of erosion*.

The terms "grade," "graded plain," and "base-level" and "base-leveled plain," are somewhat variously, and therefore somewhat confusingly used. "A graded valley is one in which there is a condition of essential balance between corrosion and deposition."¹ Its angle of slope is variable and is dependent on the capacity of the stream for work, and on the work it has to do. A weak river must have a higher gradient than a strong one; a stream with much sediment must have a higher gradient than one with little, and a stream with a load of coarse material must have a higher gradient than one with a load of fine. Thus the graded valley of the lower Mississippi has an inappreciable angle of slope; but the graded valleys of some of its small tributaries have slopes of hundreds of feet per mile. Since both the size of the stream and the amount and coarseness of its load at a given place vary from time to time in the course of a cycle of erosion, it is clear that the inclination of a graded valley must vary. With the changing conditions of advancing years, the slope of a graded valley normally decreases. The same principles apply to graded surfaces outside of valleys.

In the continual readjustment of grades incident to a river's normal history, the land is brought nearer and nearer to sea-level. When the inclination of a graded surface becomes so low that it is sensibly flat, the surface may be said to be at *base-level*, although this does not mean that the surface can never be degraded more. If the term be used in this way, it is clear that there is no sharp line of distinction between a graded surface and a base-leveled surface. A base-leveled surface is necessarily a graded surface and all graded surfaces of low gradients are base-levels.

The ocean may be looked upon as a barrier which in a general

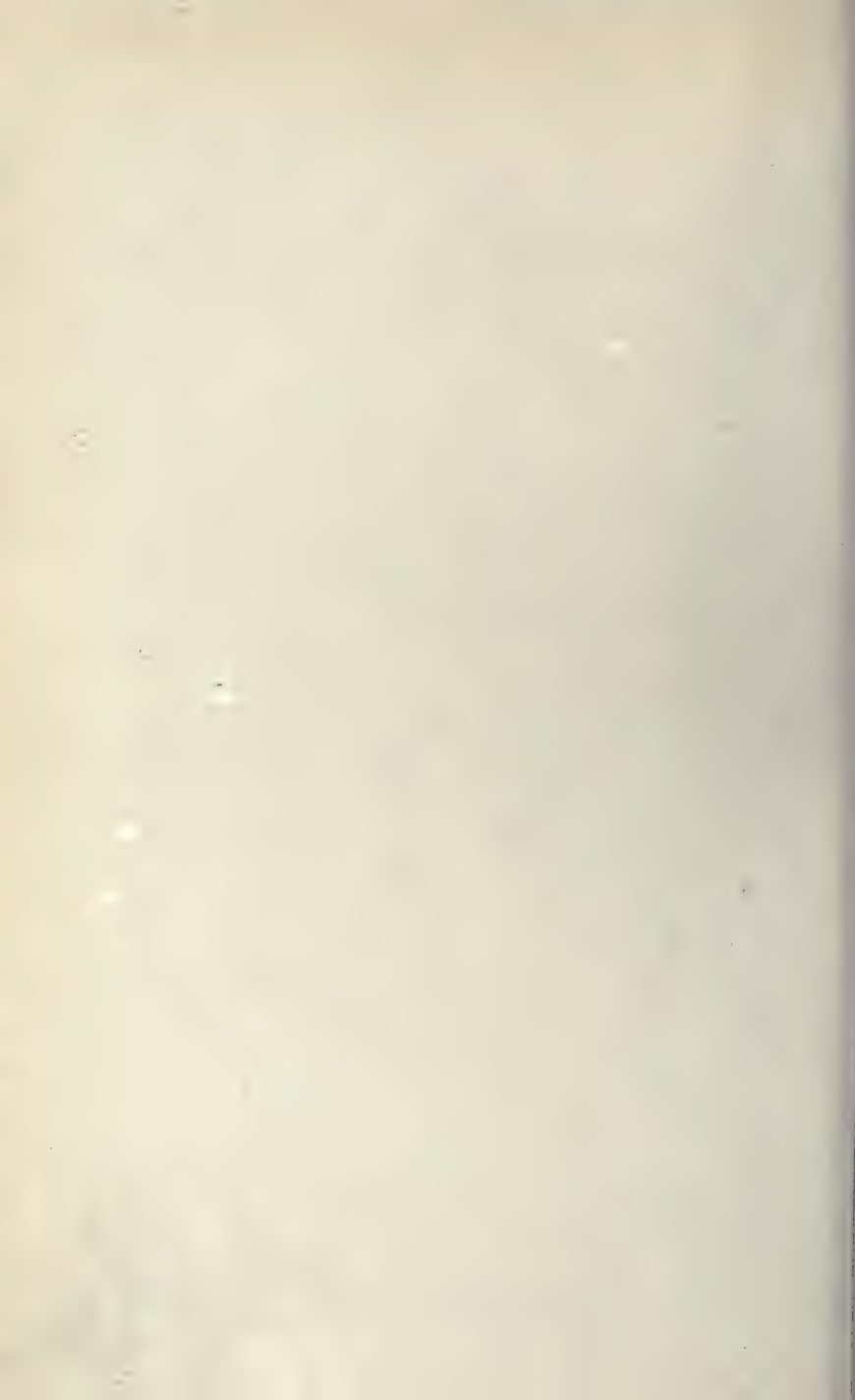
¹ Davis. Jour. of Geol., Vol. X, p. 87.



FIG. 1.—Youthful topography in a region of slight relief. The valley of Maple Creek is narrow, and much of the area is unaffected by erosion Scale, about 2 miles per inch.



FIG. 2.—A young valley in a region of great relief. Scale, about 2 miles per inch.



way limits the down-cutting of running water. Other barriers, such as lakes, and the outcrops of hard rock in a stream's bed, have a comparable, though more temporary, effect on the development of valley plains above themselves. Plains thus developed have been called *temporary base-levels*.

Stages in a cycle of erosion. Since river valleys have a beginning and pass through various stages of development before the country they drain is base-leveled, it is important to recognize their various stages of advancement. Nor is this difficult. An old valley and a young one have different characteristics, and the

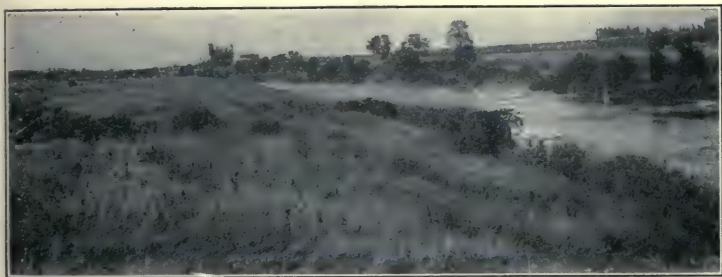


Fig. 95.— A shallow river valley in a plain. Cerro Gordo Co., Ia. Contrast with Fig. 96. (Calvin.)

one would no more be mistaken for the other by those who have learned to interpret them, than the face of an aged man would be mistaken for that of a child.

The cycle begins with the beginning of valley development, and at that stage drainage is in its *infancy*. The type of the infant valley is the gully or ravine (Fig. 72). It has steep slopes and a narrow bottom. Plate III represents somewhat older ravines in contour. The valley is widened, lengthened, and deepened, and passes from infancy to *youth*. In this stage also the valleys are relatively narrow, and the divides between them broad. They may be deep or shallow, according to the height of the land in which they are cut, and the fall of the water flowing through them; but in any case the streams flowing through them have done but a small part of the work they are to do before the country they

drain is base-leveled. Figs. 95 and 96, respectively, represent youthful valleys in regions of moderate and great relief. Fig. 1, Pl. VI shows youthful valleys in a region of slight relief, and Fig. 2, Pl. VI, in a region of great relief. The uppermost line in Fig. 89 likewise represents topographic youth, as shown in cross-profile.



Fig. 96.— The canyon of the Yellowstone below the falls. Yellowstone National Park.

Not only are narrow valleys said to be young, but the territory affected by them is said to be in its *topographic youth*, since but a small part of the time necessary to reduce it to base-level has elapsed. An area is in its topographic youth when considerable portions of it are still unaffected by valleys. Thus the areas (as

a whole), as well as the valleys, represented on Plate VI, are in their topographic youth. It is often convenient to recognize various sub-stages, such as early youth, middle youth, and late youth, within the youthful stage of valleys or topographies.

Youthful streams, as well as youthful topographies, have their distinctive characteristics. They are usually swift; their cutting is mainly at the bottom rather than at the sides, and their courses are often marked by rapids and falls.

As valleys approach base-level, they develop flats. As the



Fig. 97.— A valley much older than that shown in Fig. 96, Gray Copper Gulch, southwestern Colorado. (U. S. Geol. Surv.)

valleys and their flats widen, and as their tributaries increase in numbers and size, a stage of erosion is presently reached where but little of the original upland surface remains. The country is largely reduced to slopes, and in this condition the drainage and the topography which it has determined are said to be *mature*. Mature topography is shown in contours in Pl. VII, where slopes, rather than upland or valley flats, predominate. Mature topography is also shown in Fig. 97, which illustrates the universal tendency of rivers in regions of notable relief to develop new flats well below the former surface of the region.

The same processes which have made young valleys mature will in time work further changes. When the gradients of the valleys

have become low and their bottoms wide, and when the intervening ridges and hills have become narrow and small, the drainage and the drainage topography have reached *old age*. This is illustrated by Pl. VIII, and in section by the third and lower lines in Fig. 89. Topographic old age sometimes has a different expression; this is shown in Fig. 98, where most of the surface has been brought low. The elevations which rise above the general plain are small in area, but have abrupt slopes. This phase of old-age topog-

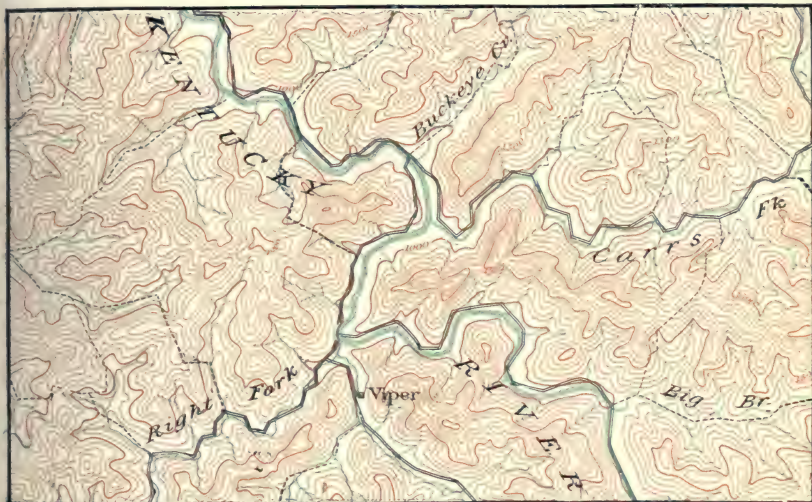


Fig. 98.— A peneplain near Camp Douglass, Wis. (Atwood.)

raphy is usually the result of the unequal resistance of the rock degraded.

The marks of old streams are as characteristic as those of young ones. They have low gradients and are sluggish. Instead of lowering their channels steadily, they cut them down in flood, and fill them up when their currents are not swollen. They meander widely in their flat-bottomed valleys (Pl. VIII) and their erosion, except in time of flood, is largely lateral.

The preceding discussion, and the illustrations which accompany it, give some idea of the topography which characterizes an area in various stages of its erosion history. Whether the valleys are deep or shallow in youth and maturity, and whether the intervening ridges are high or low, depends on the original height of the land and its distance from the sea. The higher the land, and the nearer it is to the sea, the greater the relief developed by erosion.



A region in a mature stage of erosion. Scale, about 2 miles per inch.
(Kentucky, U. S. Geol. Surv.)

PLATE VIII

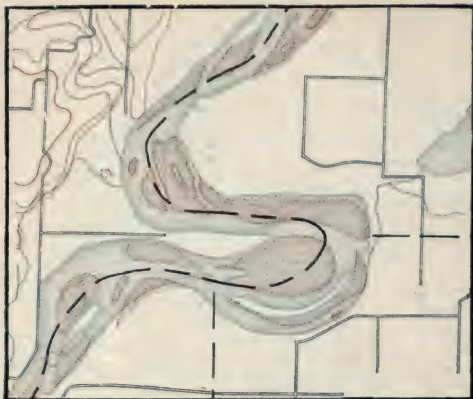


FIG. 1.—A meandering stream. The Missouri River. Scale, about 2 miles per inch. (Marshall, Mo., Sheet, U. S. Geol. Surv.)

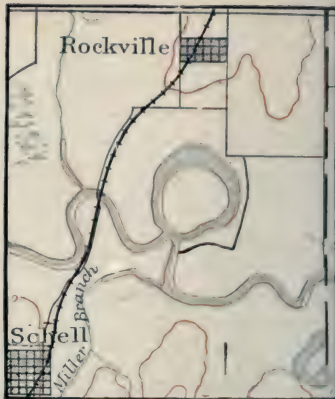


FIG. 2.—A stage in the development of a meander. Schell River. Scale about 2 miles per inch. (Butler, Mo., Sheet, U. S. Geol. Surv.)

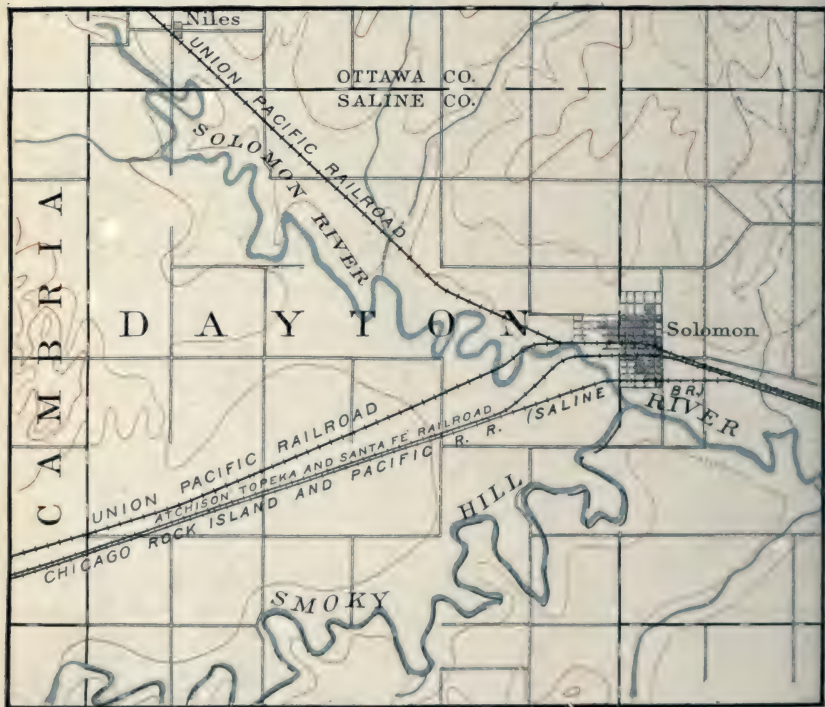


FIG. 3.—A plain in old age. Scale, about 2 miles per inch. (Abilene, Kan., Sheet, U. S. Geol. Surv.)

A plateau near the sea may become mountainous in the mature stage of its erosion history, while a plain in the same situation would only become hilly. A plateau in the heart of a continent would have less relief in its maturity than one of equal elevation near the sea, since the grade-plain in the former position is higher than in the latter.

General Characteristics of Topographies Developed by River Erosion

With the characteristics of river valleys and the methods by which they grow clearly in mind, it is easy to say whether rivers have been the chief agents in the development of a given topography. River valleys are distinguished from other depressions on land surfaces by their linear form, and, leaving out of consideration the relatively insignificant inequalities in streams' channels, by the fact that any point in the bottom is lower than any other point farther up stream in the same valley, and higher than any point farther down stream. The second point might be otherwise stated by saying that every valley excavated by erosion leads to a lower valley, to the sea, or to an island basin. Streams which dry up, or otherwise disappear as they flow, constitute partial exceptions. If, therefore, the depressions on a land surface are linear, lead to other and deeper valleys, and finally to an inland basin, or the sea, and if the elevations between these valleys are such as might have been left by the excavation of the valleys, it is generally clear that rain and rivers have been the chief factors in the development of the topography. If, on the other hand, a surface is characterized by topographic features which streams cannot develop, such as enclosed depressions, or hills and ridges whose arrangement is independent of drainage lines, other agents besides rain and surface streams have been concerned in its development.

Special Features Resulting from Special Conditions of Erosion

Many striking topographic and scenic features result from rain and river erosion. Some of them depend primarily on the conditions of erosion, such as climate, altitude, etc., while others depend largely on the structure and resistance of the rock.

Bad-land topography. A type of topography developed in early maturity in certain high regions where the rock is but slightly though unequally, resistant, is termed *bad-land topography*. Some

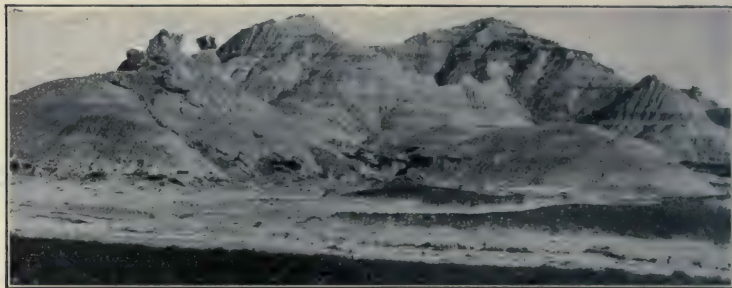


Fig. 99.— Bad lands of South Dakota. Oligocene formation. (Williston.)

idea of bad-land topography is gained from Figs. 99 and 100. Bad-land topography is found in various localities in the West, but especially in western Nebraska and Wyoming, and the western



Fig. 100.— Bad-land topography north of Scott's Bluff, Neb. (Darton, U. S. Geol. Surv.)

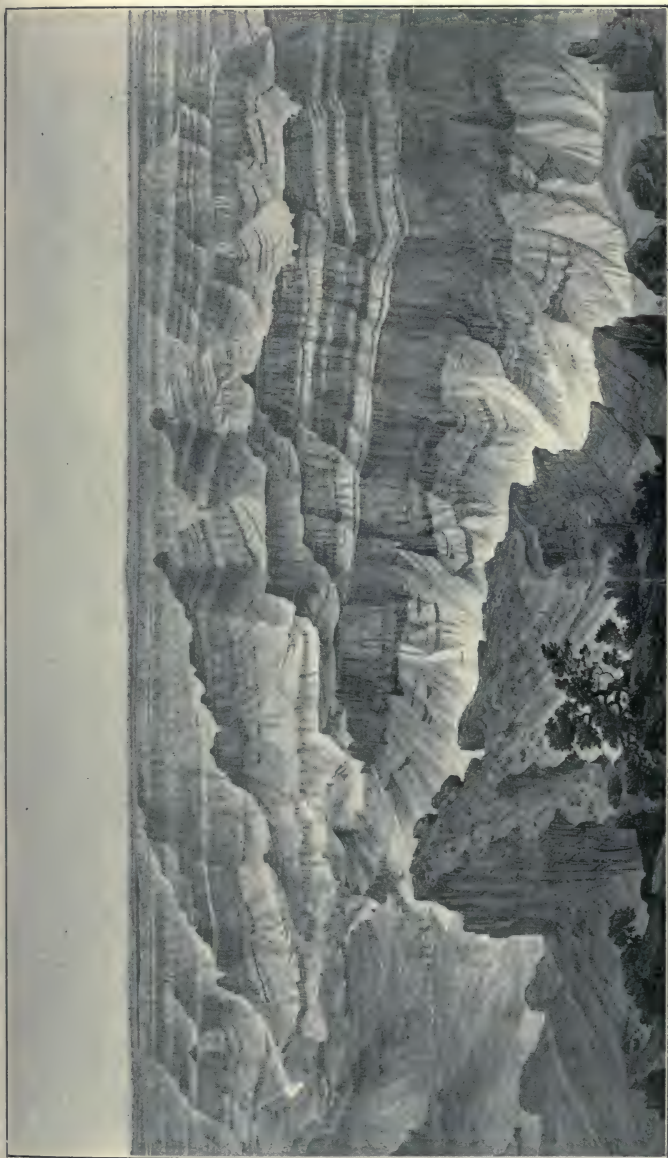


Fig. 101.—Sketch of a part of the Grand Canyon of the Colorado. A glimpse of the river is to be had at the left.
(Holmes, U. S. Geol. Surv.)

parts of the Dakotas. The formations here are often beds of sandstone or shale, alternating with beds of clay. Climatic factors are also concerned in the development of bad-land topography. A semi-arid climate, where the precipitation is much concentrated, seems to be most favorable for its development. The bad-land topography is most striking in early maturity.

Special forms of valleys; canyons. Various conditions influence the size and shape of valleys, especially in the early stage of their

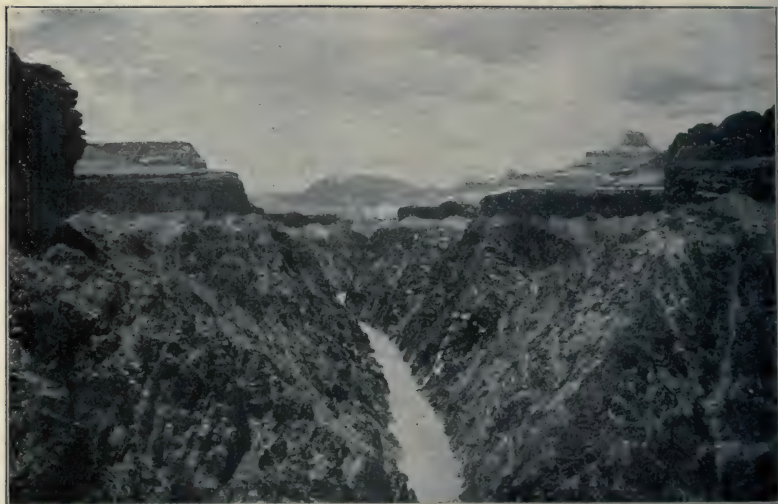


Fig. 102.— Grand Canyon of the Colorado. (Peabody.)

development. High altitude of land favors swift flowing streams, and the development of deep valleys. Such valleys will be narrow if the conditions which determine widening are absent or unfavorable. An arid climate favors the development of narrow valleys if there is sufficient water to maintain a vigorous stream, because there is little slope wash. Narrow valleys with steep slopes will also be favored if the valley is cut in rock which is capable of standing with steep faces. Thus a stream may develop a narrow valley in firm rock where it would not do so in loose gravel. Aridity, high altitude, and the proper sort of rock structure therefore favor

the development of canyons, and many of the young valleys in the western part of the United States where these conditions prevail, belong to this class.

While all canyons are valleys, most valleys are not canyons. In popular usage, the rule seems to be that if a valley is sufficiently deep, narrow, and steep-sided to be distinctly striking, it is called a canyon in regions where that term is in use. Whether a valley is deep, narrow, and steep-sided enough to be striking, clearly depends on the observer. The Colorado Canyon (Figs. 101 and 102) is the greatest canyon known, but it is rarely more than a mile deep, and where its depth approaches this figure it is often 8, 10, or



Fig. 103.—Diagram showing the proportions of a valley the width of which is eight times the depth. These are approximately the proportions of the Colorado Canyon.

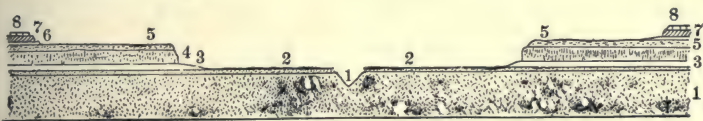


Fig. 104.—Cross-section of the Colorado Canyon. (After Gilbert and Brigham.)

even 12 miles wide from rim to rim. Its width at bottom is little more than the width of the stream; that is, a few hundred feet. Its cross-profile throughout much of its course is therefore not in keeping with the conventional idea of a canyon. With a depth of one mile and a width of eight, the slope, if uniform, would have an angle of less than 15° . Such a valley is represented in Fig. 103. As a matter of fact the slopes of a canyon are not commonly uniform, but more like those of Fig. 104. The step-like slopes are due to inequalities of hardness. It is perhaps needless to say that to an observer on the rim of the canyon, the slopes seem several times as steep as those shown in the diagrams.

Like all valleys which are narrow relative to their depth, the Colorado Canyon, great as it is, is a young valley, for it represents but a small part of the work which the stream must do to bring its drainage basin to base-level.

While aridity and altitude are conditions which favor the development of canyons, as shown by the fact that most canyons are in high and dry regions, they are not indispensable. Niagara River has a canyon below its falls (Pl. IX), and the surrounding region is neither high nor arid. The narrow-part of the valley is so young that side erosion has not yet widened the valley or lowered its angle of slope to such an extent as to destroy its canyon character. This canyon is often called a *gorge*, a term frequently applied to small valleys of the canyon type.

Rate of Degradation

The amount of mechanical sediment which the Mississippi River carries to the Gulf of Mexico is estimated to represent a rate of degradation for the Mississippi basin of about one foot in 5,000 years. But the mechanical sediment carried to the Gulf does not really represent the total degradation of the basin, for the water which sinks beneath the surface is dissolving more or less rock substance, especially lime carbonate. This material is carried to the sea in solution, and does not appear in the sediment on which the above estimate is based. Taking into account the matter dissolved by the water and carried to the sea in solution, the average rate of degradation for the Mississippi basin has been estimated at one foot in 3,000 to 4,000 years.¹

The sediment carried to the Gulf by the Mississippi River is gathered from nearly all parts of the basin of this stream, but much more of it comes from some parts of the basin than from others. On the whole, the rate of erosion is probably greatest toward the margins of the basins, where the land is in its topographic youth or early maturity. It is notably less in the middle courses of the valleys, and is exceeded by deposition in some places along the lower courses of the Mississippi and some of its main tributaries.

The average elevation of North America is probably not far from 2,000 feet. If the present rate of degradation, say one foot in 3,500 years, were to continue, it would take something like

¹Some recent unpublished data seems to indicate that this rate is, perhaps, too high.

7,000,000 years to bring the continent to sea-level. But this rate of degradation could not continue to the end, for as the continent became lower, streams would become sluggish and erosion less rapid. Long before the continent reached base-level, the rate of degradation, so far as dependent on mechanical erosion, would become so slow that the time necessary to bring the continent to sea-level would be indefinitely prolonged. Furthermore, it is quite possible that the land is suffering, or is liable to suffer, uplift, relative or absolute. If the rate of rise were equal to the rate of degradation, the average height of the continent would of course not be affected.

The following table¹ gives the percentage of material carried in suspension by various rivers:

River	Drainage areas in square miles	Mean annual discharge (in cubic feet) per second	Total tons of sediment carried to sea annually	Ratio of sediment to water by weight	Height in feet of column of sediment with a base of one sq. mile	Thickness of sediment in inches if spread over drainage area
Potomac . . .	11,043	20,160	5,557,250	1: 3,575	4.0	.00433
Mississippi . .	1,244,000	610,000	406,250,000	1: 1,500	241.4	.00223
RioGrande . .	30,000	1,700	3,830,000	1: 291	2.8	.00116
Uruguay . . .	150,000	150,000	14,782,500	1:10,000	10.6	.00085
Rhone	34,800	65,850	36,000,000	1: 1,775	31.1	.01075
Po	27,100	62,200	67,000,000	1: 900	59.0	.01139
Danube	320,300	315,200	108,000,000	1: 2,880	93.2	.00354
Nile	1,100,000	113,000	54,000,000	1: 2,050	38.8	.00042
Irrawaddy . .	125,000	475,000	291,430,000	1: 1,610	209.0	.02005
Mean	334,693	201,468	109,649,972	1: 2,731	76.65	.00614

The composition of rain-water falling near London, as determined by analysis, was as follows:²

Organic carbon	.99 part in 1,000,000 of water
Organic nitrogen	.22 " " " " "
Ammonia	.50 " " " " "
Nitrogen as nitrates and nitrites	.07 " " " " "
Chlorine	6.30 parts in " " "
Total solids	39.50 " " " " "

¹ Babb. Science, Vol. XXI, p. 343. 1893.

² Quoted by Mason. Water-supply, p. 204.

A comparison of the composition of rain-water with that of springs and rivers gives some idea of the solvent work of water. From a study of the water of 19 of the principal rivers of the world Murray has compiled the following table¹ showing the amount of mineral matter in average river water:

Constituents	Tons in a Cubic Mile
Calcium carbonate (CaCO_3)	326,710
Magnesium carbonate (MgCO_3)	112,870
Calcium phosphate ($\text{Ca}_3\text{P}_2\text{O}_8$)	2,913
Calcium sulphate (CaSO_4)	34,361
Sodium sulphate (Na_2SO_4)	31,805
Potassium sulphate (K_2SO_4)	20,358
Sodium nitrate (NaNO_3)	26,800
Sodium chloride (NaCl)	16,657
Lithium chloride (LiCl)	2,462
Ammonium chloride (NH_4Cl)	1,030
Silica (SiO_2)	74,577
Ferric oxide (Fe_2O_3)	13,006
Alumina (Al_2O_3)	14,315
Manganese oxide (Mn_2O_3)	5,703
Organic matter	79,020
Total dissolved matter.	762,587

The 6,500 cubic miles of river water, which Murray estimates flows to the sea annually, would carry about 4,975,000,000 tons of mineral matter in solution.

ANALYSIS OF EROSION²

Erosion is the term applied to all the processes by which earthy matter or rock is loosened or removed from one place to another. It consists of several sub-processes, namely, *weathering*, *transportation*, *corrasion*, and *corrosion*.

Weathering

Weathering is the term applied to nearly all those natural processes which tend to loosen or change the exposed surfaces of rock.

¹ Scot. Geol. Mag., Vol. III, p. 76. 1887.

² An excellent discussion of this subject is given by Gilbert in *The Henry Mountains*, pp. 99 et seq., and more briefly in the *Am. Jour. Sci.*, Vol. XII, p. 85, et seq., 1876.

The lettering of inscriptions on exposed marble becomes fainter and fainter as time goes by, and finally disappears, because the rock in which the letters were cut has weathered away. In this case the weathering is effected partly by the atmosphere and partly by water, and these are the chief, though not the only agents concerned in weathering.

The rain which falls upon the surface of exposed rock, and that which sinks through the soil to the solid rock below, dissolves slowly some of the constituents of the rock. This tends to make the rock crumble, much as mortar does when the lime carbonate which cements the sand is dissolved. The chemical changes effected by ground-water and the gases dissolved in it, also help to disintegrate the rock, as we have seen.

There are other processes of weathering not due directly either to the atmosphere or to water. Thus the roots of trees frequently grow into cracks of rocks (Fig. 105), and, increasing in size, act like wedges. Again, water freezing in cracks works in the same way.

From the faces of steep cliffs masses of rock are frequently loosened, by the wedge-work of roots or ice, or by expansion and contraction due to changes of temperature. The quantities of debris at the bases of many cliffs, forming slopes of *talus* (Fig. 106), testify to the importance of the weathering of the rock, and to the action of gravity in getting loosened material down. Another phase of gravity work is shown in Fig. 107. Here, under the influence of gravity and expansion and contraction, due to freezing and thawing and wetting and drying, the surface material is creeping down slope. In the process the rock is being broken. The descent of rock detritus under the influence of gravity is hardly weathering, but it is often weathered material which is brought down.



Fig. 105.— Tree growing in crack in a rock, and by its growth splitting the rock.



Fig. 106.—Talus slope, Utah.



Fig. 107.— Shows the downward creep of soil and slaty rock under the influence of gravity. (U. S. Geol. Surv.)

The above are among the commoner processes of weathering, although they do not exhaust the list. The more active and tangible processes by which surface rocks are broken up, such as wave wear, river wear, and glacier wear, are processes of corrasion, and are not usually regarded as processes of weathering.

The importance of weathering in the general processes of erosion is shown in many ways. In regions where the mantle rock is the product of the decay of the solid rock beneath, and such regions constitute a large portion of the earth's surface, the soil and subsoil represent the excess of weathering over transportation. Since most of the earth's surface is covered with soil and subsoil, it is clear that, on the whole, weathering keeps ahead of transportation. Again, it is clear that the loosening of rock by weathering greatly increases the erosion which a given amount of moving



Fig. 108.—Diagram of a valley, the top of which is ten times the width of the stream.

water can accomplish. Not only this, but weathering plays a much more important rôle in the development of valleys than is commonly realized. This is illustrated by the valleys of young swift streams. The valley whose top is not ten times as wide as its stream, is rare. The stream which has such a canyon has been cutting chiefly at its bottom. A swift stream would make a valley as wide as itself. This is illustrated by Fig. 108. Weathering in its broadest sense is largely responsible for the width of such a valley, in so far as it exceeds the width of the stream. Weathering, slope wash, etc., have widened the valley, especially in its upper part, and the stream has carried away the material which slope wash, gravity, etc., brought down to it. The above illustration would not apply to old and sluggish streams, for they widen their valleys by meandering, independently of weathering.

The central idea of the processes embraced under the term weathering is the loosening and the disrupting of rock, by which

it is prepared for transportation. Weathering is the first step in most erosion, but it is not the only one, and erosion may take place without it.

Transportation

A second element of erosion is transportation. The transportation of sediment is to be distinguished from the transportation of materials in solution. In so far as mineral matter is dissolved, it becomes a part of the fluid of the stream. If the quantity dissolved were large, it might influence the mobility of the water; but the amount is usually too slight to influence flow sensibly.

The sediment transported by a stream is either rolled along its bottom, or carried in suspension above the bottom. The coarser materials (gravel and sand) are carried chiefly in the former position, and the finer (silt and mud) largely in the latter.

Transporting power and velocity. The transporting power of running water depends on its velocity. Swift streams have enormously greater power of transportation than sluggish ones, but transportation does not always keep pace with transporting power. The Niagara at its rapids is a stream of great transporting power, but it carries little sediment, because there is little to be had.

The velocity of a stream depends chiefly on three elements — its gradient, its volume, and its load. The higher the gradient, the greater the volume, and the less the load, the greater the velocity. The relation between gradient and velocity is evident; that between volume and velocity is illustrated by every stream in time of flood, when its flow is greatly accelerated. The relation between velocity and load is less obvious, but none the less definite. Every particle of sediment carried by a stream makes a draught on its energy, and energy expended in this way reduces the velocity. A muddy stream is never so swift as a clear stream of the same size would be, flowing in the same channel.

How sediment is carried. Coarse materials, such as gravel and stones, are rolled along the bottom of the swift streams which carry them. Their movement is by the impact of the water. The same is true to a large extent of sand grains. So far as concerns the material rolled along the bottom, it is to be noted that a stream's transporting power is dependent on the velocity of the water and

its bottom. This is much less than the surface velocity, or even the average velocity.

The particles of fine sediment, such as silt and mud, are frequently carried by streams quite above their bottoms, as shown by the muddiness of many streams. Most particles of mud are small bits of mineral matter, the specific gravity of which is between two and three times that of water. Why do they not sink through the water and come to rest at the bottom of the stream?

A particle of sediment in running water is subject to two principal forces, that of the current which tends to move it nearly horizontally down stream, and that of gravity which tends to carry it to the bed of the stream. As a result of these two forces, the particle tends to move in the general direction which represents the resultant of these forces (Fig. 109). If a river were the simple

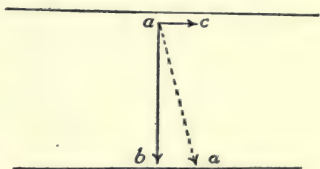


Fig. 109.— Diagram to illustrate the relative strength of the two forces acting on a particle in suspension. The arrows represented by full lines show the relative strength of the two forces when the stream's velocity is about 5 miles per hour. No account is taken in the diagram of the viscosity of the water, or of the acceleration of velocity of fall.

straightforward current which it is popularly thought to be, a particle in suspension would reach its bottom in the time it would take to sink through an equal depth of still water; for the descent would be none the less certain and scarcely less prompt because

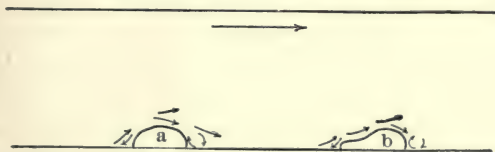


Fig. 110.— Diagram to illustrate the effect of irregularities, *a* and *b*, in a stream's bed, on the current striking them.

of the forward movement of the water. The current would simply be a factor in determining the position of the particle when it reached the bottom, not the time of reaching it. Very fine particles, like those of clay, sink less readily than coarser ones, like grains of

sand, because the former expose larger surfaces, relative to their mass, to the water through which they sink. But even such particles, unless of extraordinary fineness, would presently reach the bottom if acted on only by a horizontal current and gravity. Since even sediment which is not of exceeding fineness is kept in suspension, it is clear that some other factor is involved. This is found, in part at least, in the subordinate upward currents in a stream.

Where a boulder occurs in the bed of a stream (Fig. 110) a part of the water which strikes it is forced up over it. If there are many boulders, the process is frequently repeated, and the number of upward currents is great. Any roughness will serve the same purpose, and every stream's bed is rough to a greater or less extent. Roughnesses at the sides of a channel start currents which flow toward the center, and the varying velocities of the different parts of a stream serve a similar purpose. A river is therefore to be looked upon as a multitude of currents, some rising from the bottom toward the top, some descending from top to bottom, some diverging from the center toward the sides, and some converging from the sides toward the center.

It is, of course, true that the sum of the upward currents is always less than the sum of the downward, so that the aggregate motion of the water is down slope. Sediment in suspension is held up chiefly by the upward currents, which, locally and temporarily, overcome the effect of gravity. The particles in suspension are constantly tending to fall, and frequently falling; but before they reach the bottom, many of them are seized and carried upward by the subordinate currents, only to sink and be carried up again. Even if they reach the bottom, as they frequently do, they may be picked up again. It is probable that every particle of sediment of such size that it would sink readily in still water is dropped and picked up many times in the course of any long river journey, and its periods of rest often exceed its periods of movement.

Corrasion

The mechanical wear effected by running water is *corrasion*. So long as the materials to be moved are incoherent, it is easy to understand how running water moves them. The water which

flows over the surface of a cultivated field gathers earthy matter, and the process is continued all the way to the channel of the stream. Thus sediment is gathered at the very sources of the streams. It is also contributed by all slope wash from whatever part of the valley, and the stream gathers more load from its bed wherever it flows with sufficient velocity over loose material. Streams also undercut their banks, and receive new load from the fall of the overhanging material.

By far the larger part of the sediment of most streams is made up of material loosened in advance by the processes of weathering. The stream, and the waters which get together to make the stream, find them ready-made; but rivers frequently wear rock which is not weathered, for the principal valleys of the earth are in solid rock, and many of them in rock of great hardness. How does the stream wear the solid rock?

When a stream flows over a rock bed, the wear which it accomplishes depends chiefly on the character of the rock, the velocity of the stream, and the load it carries. If the rock is much divided by bedding planes and joint planes, the water of a clear stream of even moderate strength may dislodge bits of the rock. This condition of things is often seen where streams run on beds of shale or slate. If the rock is hard and without bedding-planes and joints, or if its layers are thick and its joints few, clear water will be much less effective. If massive hard rock presents a smooth surface to a clear stream, the mechanical effect of even a swift current is slight.

This general principle is illustrated by the Niagara River. Just above the falls the current is swift. When the river is essentially free from sediment, the surface of the limestone near the bank beneath it is sometimes distinctly green from the presence of the one-celled plants (fresh-water algæ) which grow upon it. The whole force of the mighty torrent is not able to sweep them away. Were the stream supplied with a tithe of the sand which it is capable of carrying, it would not take many hours, and perhaps not many minutes, to remove the last trace of the vegetation. This illustration furnishes a clue to the method by which the erosion of solid rock in a stream's bed is effected.

The gravel rolled along the channel wears even solid rock, and as the moving stones wear the stream's bed, they are themselves worn by impact both with the bed and with one another, and are reduced to rounded, water-worn forms. The particles broken off may make grains of sand, or, if very fine, particles of silt or mud. In the course of time the pebbles and cobbles rolled along may be literally worn out.

The sediment carried in suspension, as well as that rolled along the bottom, wears the rock bed of a stream. The coarser the sediment and the stronger the current, the greater the wear. Contemporaneous processes are largely concerned in making valleys wide, but the depth of valleys cut in solid rock is chiefly the result of the impact and friction of the sediment in transportation. The gravel, sand, and mud carried by a stream are therefore the tools with which it works. Without them it is relatively impotent, so far as the abrasion of solid rock is concerned; with them, the stream may wear any rock over which it passes.

Swift and slow streams corrade their valleys differently. The erosion of a swift stream is chiefly at the bottom of its channel. The sluggish stream lowers its channel less rapidly, while lateral erosion is relatively more important. The result is that slow streams increase the width of their valleys more than the depth, while swift streams increase the depth more than the width. It follows that slow streams develop flats, while swift ones do not. Not only is a slow stream more likely to have a flat, and therefore a better chance to meander, but it is more likely to take advantage of opportunities in this line, for a slow stream gets out of the way for such obstacles as it may encounter, while a swift stream is much more likely to get obstacles out of its way.

Corrosion (Solution, etc.)

In most cases the solution (and other chemical changes) effected by a stream is much less important than its mechanical work. Only when conditions are unfavorable for the latter is solution the chief factor in the excavation of a valley. This may be the case where a stream's bed is over soluble rock, such as limestone, and where the stream is clear, or its gradient so low that its current is

sluggish. The solvent power of water is not influenced by the presence of sediment, though the presence of sediment offers the water a greater surface on which to work.

CONDITIONS AFFECTING THE RATE OF EROSION

Declivity

In general the greater the slope the more rapid the rate of erosion by running water, whether in the stream's channel or on the slopes above it. But high declivity does not favor every element of erosion. The effect of declivity on weathering is far from simple. Steep slopes favor some phases of weathering and hinder others, but they favor both transportation and corrasion.

Both corrasive power and transportive power increase rapidly with increase of velocity, and under these circumstances, corrasion will also be increased if the water has tools to work with, and transportation if there is material which can be carried. Since high declivity greatly increases both the transporting and the corradng power of running water, and favors certain elements of weathering, it is clear that the aggregate effect of high declivity is to favor erosion.

Rock

The physical constitution, the chemical composition, and the structure of a rock formation, influence the rate at which it may be broken up and carried away.

Physical constitution. Clastic rocks may be firmly cemented, or their constituents may be bound together loosely. The less the coherence the more ready the disintegration, and the finer the particles the more easily they are carried away. If the materials carried are harder than the bed over which they pass, corrasion of the latter is favored.

Chemical composition. Something also depends on the chemical composition of the rock, since this affects its solubility and its rate of decomposition. The more soluble the rock, the larger the proportion of it which will be taken away in solution; but it does not follow that the most soluble rock will be most rapidly eroded, since the rate of erosion depends on abrasion as well as solution, and

a rock which is readily soluble, as rocks go, may be less easily abraded than a rock which is made of discrete and insoluble particles bound together by a soluble cement. In such rocks, for example a conglomerate in which the pebbles are cemented together by lime carbonate, the solution of the cement sets free a considerable quantity of gravel, so that a small amount of solution prepares a large amount of sediment for removal. A stream might cut its valley much more rapidly in such rock than in a compact limestone, though the latter is, as a whole, the more soluble.

Structure. The structure of the rock has much to do with the rate of its erosion. Other things being equal, stratified rock is more readily eroded than massive rock, since stratification planes are planes of cleavage, and therefore of weakness. Taking advantage of these planes, the water has less breaking to perform to reduce the material to a transportable condition. For the same reason, a thin-bedded formation is more easily eroded than a thick-bedded one.

The beds of stratified rock may be horizontal, vertical, or inclined, and inclined strata may stand at any angle between horizontality and verticality. In indurated formations the rate of erosion is influenced both by the position of the strata and by the relation of the direction of the flowing water to their dip and strike. On the whole, the strata which are horizontal, or but slightly inclined, are probably less favorably situated for rapid erosion than those which are vertical or inclined at considerable angles. This is at least true where the layers are of uniform hardness and the joints infrequent. In general, joints have somewhat the effect of bedding planes, so far as erosion is concerned.

The Influence of Climate

Climate has both a direct and an indirect effect on erosion. Its direct influence is chiefly through precipitation, changes of temperature, and wind; its indirect, through vegetation. Like declivity and rock structure, climate does not affect all elements of erosion equally.

Direct effects. The effects of variations in temperature on rock weathering have been discussed in Chapters II and III.

High temperature favors chemical action, and the weathering of rock by decomposition is at its best in the presence of abundant moisture, in regions where the temperature is uniformly high. Furthermore, a warm, moist climate favors the growth of vegetation, the decay of which supplies the water with organic acids which greatly increase its solvent power. The climatic conditions favoring mechanical weathering are therefore different from those favoring chemical weathering. High temperature and abundant moisture and vegetation are found in many tropical regions, and here the rock is decomposed to greater depths, on the average, than in high latitudes. How far this is the result of rapid weathering, and how far of slow removal, due in part to the protective influence of the plants, cannot be affirmed.

So long as the water of the surface and that in the soil remains unfrozen, temperature affects neither corrosion nor transportation. But in middle and high latitudes the surface is frozen for some part of each year. During this time corrosion is at a minimum, for although the streams continue to flow, there is relatively little water running over the surface outside the drainage channels, and that little is relatively ineffective. Under some conditions, therefore, temperature affects both corrosion and transportation.

The humidity of the atmosphere has an influence even more important than that of temperature upon the rate of erosion, and its influence is exerted on each of the elements of that complex process. A moist atmosphere favors oxidation, carbonation, hydration, and the growth of vegetation, all of which promote certain phases of rock weathering. On the other hand, humidity tends to prevent sudden and considerable variations in temperature, thus checking the weathering effected by this means. Precipitation, the most important single factor in determining the rate of erosion, is dependent on atmospheric humidity. Its amount, its kind (rain or snow), and its distribution in time, are the elements which determine its effectiveness in any given place.

Other things being equal, the greater the amount of precipitation the more rapid the corrosion and transportation. Much, however, depends on its distribution in time. A given amount of rainfall may be distributed equally through the year, or it may fall

during a wet season only. The maximum inequality of distribution would occur if all the rainfall of a given period were concentrated in a single shower. With such concentration the volume of water flowing off over the surface immediately after the down-pour would be greater than under any other conditions of precipitation, and since velocity is increased with volume, and erosive power with velocity, it follows that the erosive power of a given amount of water would be greatest under these circumstances. Furthermore a larger proportion of the precipitation would run off over the surface under these circumstances than under any other, for less of it would sink beneath the surface, and less would be evaporated.

If erosive power and rate of erosion were equal terms, the maximum concentration of rainfall would be the condition for greatest erosion; but erosive power and rate of erosion do not always correspond. If the water falling in this way could get all the material it could carry, erosion would be at a maximum; but if the amount of available material for transportation is slight, a large part of the force of the water could not be utilized in erosion. In this case, that distribution of precipitation which most favored weathering would lead to greatest erosion. Temperature favoring, the uniform distribution of moisture through the year would allow the growth of vegetation. This would favor some processes of weathering, but it would retard erosion in general. While, therefore, it is hardly possible to say what distribution of rainfall favors most rapid erosion without knowing the nature of the surface on which it is to fall, enough has been said to show that the problem is not a simple one. Some of the most striking phases of topography developed by erosion, such as those of the Bad Lands (Figs. 99 and 100), are developed where the rainfall is unequally distributed in time, and too slight or too infrequent to support abundant vegetation.

Except in dry regions, where wind-work sometimes exceeds water-work, the movements of the atmosphere are of less importance directly than precipitation in determining the rate of erosion. But even in regions which are not arid the winds have much to do with the rate of evaporation and the distribution of rainfall, so that their indirect effect is great.

Erosion in arid regions differs from that in regions of abundant rainfall in several ways. It is obvious that the valleys will develop more slowly in the former, that they will remain young longer, that the period necessary for the dissection of the surface is greater, that the water-courses will be less numerous, and that fewer of them will have permanent streams. There are certain other differences which are less obvious. If the arid region is high and composed of heterogeneous strata, the topography which erosion develops is more angular (Figs. 101 and 133) than that of the humid region. This is because there is less rock decay, and less vegetation to hold the products of decay. The more resistant beds of rock, therefore, come into greater prominence, especially on slopes, where they develop cliffs (Figs. 101 and 104). These general principles find abundant illustration in the plateaus of the western part of the United States,¹ where cliffs are by no means confined to the immediate valleys of the streams.

Indirect effects. Through vegetation, climate influences erosion in ways which are easily defined qualitatively, but not quantitatively. Both by its growth (wedge-work of roots) and by its decay (supplying CO₂, etc., to descending waters) it favors certain phases of weathering; but, on the other hand, it retards corrasion and transportation both by wind and water. This is well shown along the banks of streams and on the faces of cliffs, in clay, sand, etc. Its aggregate effect is probably unfavorable to erosion by mechanical means, and favorable to that by chemical processes.

EFFECTS OF UNEQUAL HARDNESS

Irregularities of hardness give rise to many peculiarities of topography, and to many scenic features. To this category belong many rapids, falls, narrows, terraces, and many striking hills and ridges.

Falls and rapids. Falls and rapids are most commonly developed where streams pass from more resistant to less resistant rock. The greater wear of the latter gives origin to rapids. At first the

¹ Dutton. Tertiary History of the Grand Canyon District, Mono. II, U. S. Geol. Surv.

rapids are slight (*a*, Fig. 111), but they become more considerable (*b*) as time and erosion go on. When the bed of the rapids becomes



Fig. 111.—Diagram illustrating the development of a fall where the hard layer dips up-stream.

sufficiently steep, the rapids become *falls*¹ (*cd*). When the water

falls rather than *flows* over the rock surface below the hard layer, erosion assumes a new phase. The hard layer is then undermined, and the undermining causes the falls to recede. This phase of erosion is sometimes called *sapping* (Fig. 113).



Fig. 112.—The lower fall of the Yellowstone.

If the hard layer which occasions a fall dips up-stream (Fig. 111), its outcrop in the stream's bed becomes lower as the fall recedes (*e*). When it has become so low that the water passing over it no longer reacts effectively against the less resistant material beneath (*f*), sapping ceases, and the fall is then transformed again into rapids. The history of rapids which succeed falls is the reverse of the history which preceded. The later rapids are

steepest at the beginning of their history, the earlier at their end. Stated in other terms, rapids are steepest when nearest falls in

¹ The terms *rapids*, *falls*, and *cataracts* are rather loosely used. Many moderate rapids are incorrectly called falls. The "Falls of the Ohio" is an example. The term *cataract* is often applied to very steep rapids or falls.

time. Slight differences in the resistance of successive layers often occasion successive falls or rapids (Fig. 114).

If the layers of unequal hardness in a stream's bed are vertical, and the course of the stream at right angles to the strike, rapids, and perhaps falls, will develop. Falls developed under these conditions would not recede.

The inequality of resistance in the rock which occasions a fall may be original or secondary. In the case of Niagara Falls (Fig. 113) relatively resistant limestone overlies relatively weak shale. At the Falls of St. Anthony (Minneapolis) limestone overlies

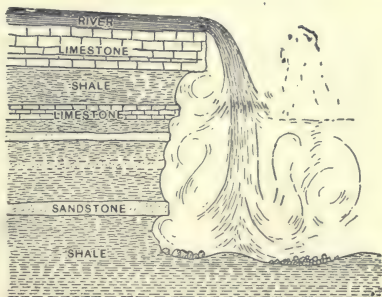


Fig. 113.—Diagram illustrating the conditions at Niagara. (Gilbert.)

friable sandstone. The falls of the Yellowstone, and the Shoshone Falls of the Snake River (Idaho), are in igneous rock. In the former case the unequal resistance is occasioned by unequal decay of the rock, due perhaps to the rise of hot vapors which have decomposed the rock along the lines of their ascent; in the latter, a more resistant sort of igneous rock overlies a less resistant.

One waterfall often breeds others. Thus where a fall recedes beyond the mouth of a tributary stream, the tributary falls. The Fall of Minnehaha creek tributary to the Mississippi near Minneapolis, is an illustration. Once in existence, the fall of a tributary follows the same history as that of a main stream.

The fall of the Niagara¹ (Pl. IX) is one of the most remarkable known both because of its large volume of water and its great descent, between 160 and 170 feet. This fall is divided into two parts, separated by Goat Island, the Horseshoe fall (Fig. 115) on the west, and the American fall on the east. Between 1842 and 1905, the Horseshoe fall receded about five feet a year, while be-

¹ For a brief account of this fall see Gilbert in *Physiography of the United States*.



A



B

Fig. 114.— A, Bridal Veil Fall, Camloops, British Columbia. B, Twin Falls, Yoho Valley, British Columbia.



Fig. 115.— Niagara Falls. (U. S. Geol. Surv.)



The Niagara Gorge. Scale, about 1 mile per inch. (Niagara Falls, N. Y. Sheet, U. S. Geol. Surv.)

PLATE X



Cusketunk and Round Mountains, New Jersey; examples of isolated mountains left by the removal of less resistant surroundings Scale, about 1 mile per inch (High Bridge Sheet, U. S. Geol. Surv.)

between 1827 and 1905, the American fall receded less than three inches a year.¹

Rapids and falls sometimes occasion the development of pot-holes (Fig. 116), a peculiar rather than important feature of erosion. The holes are excavated in part by the falling and eddying of silt-charged water, but chiefly by stones which the eddies move. Pot-



Fig. 116.— Pot-holes in granite. Upper Tuolumne River, Cal.

holes which are not now in immediate association with rapids or falls often point to the former existence of rapids or falls.

Rock terraces. Where a hard layer outcrops in the side of a valley above its bottom, the side slopes of the valley become gentle just above the hard layer, and steep, or even vertical, at and below its outcrop, as illustrated by Fig. 117. The hard layer then stands out as a rock terrace on either side of the valley. Such terraces are not rare, and are popularly believed to be old "water-lines";

¹ Gilbert. Bull. 306, U. S. Geol. Surv.

that is, to represent the height at which the water once stood. In one sense this interpretation is correct, since a river has stood at all levels between that of the surface in which its valley

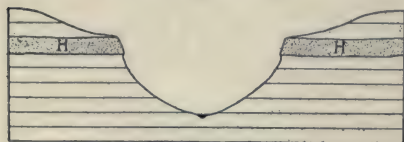


Fig. 117.— Rock terraces, due to resistant layers or rock.

started, and its present channel; but the shelf of hard rock does not mean that the river was ever so large as to fill the valley from its present channel to the level of the terrace. Rock terraces may also result from changes of level.

Narrows. If a stream crosses vertical or highly inclined strata of unequal hardness, its valley is usually constricted at the crossing of the hard layers. If such a constriction is notable it is called a *narrows*, or sometimes a *water-gap* (Fig. 118). The Appalachian Mountains afford numerous examples. The narrows develop because the processes which widen the valley are less effective on the hard layer than on the less resistant ones. Narrows sometimes arise in other ways also.

Narrows are much more conspicuous in certain stages of erosion than in others. While a valley is still so young as to be narrow at all points, there can be no pronounced “narrows”; but later, when the valley is otherwise wide, narrows are more pronounced. From



Fig. 118.— The Kittatinny Mountain and Delaware Water-Gap from Manunka Chunk. (N. J. Geol. Surv.)

what has preceded it is clear that rapids or falls are likely to occur at narrows, especially in the early part of their history.

Other effects on topography. Inequalities in the hardness of rock develop certain peculiarities of topography outside of valleys. The less resistant portions of a land area more or less distant from streams are worn down more readily than those which are more resistant. If great areas of high land be capped with hard rock, they are likely to remain as plateaus after surrounding areas of



Fig. 119.— The Enchanted Mesa. A striking butte in New Mexico. The name mesa is not commonly applied to elevations of such small summit area. (R. T. Chamberlin.)

less resistance are brought low. If the hard capping remains over a small area instead of a large one, the elevation is a butte, a hill, or a mountain, instead of a plateau (Fig. 119). Many buttes and small mesas are but remnants of former plateaus. A feature of buttes and mesas capped by hard rock is the steep slopes or *cliffs* corresponding to the edges of the hard beds (Figs. 101 and 119).

If the rock of a region is stratified and the layers tilted, the removal of the softer beds leaves the harder ones projecting above the general level in the form of ridges or “hog-backs” (Fig. 120). Dikes of igneous rock, harder than the beds which they intersect, likewise become ridges after the degradation of their surroundings. The plugs of old volcanic vents and other igneous intrusions of limited area often constitute conspicuous hills or mountains after

erosion has removed their less resistant surroundings (Fig. 121). Round Valley, shown on Pl. X, is an example.

Ridges and hills resulting from the unequal degradation of unequally resistant strata are not equally prominent at all stages in an erosion cycle. In early youth the material surrounding the hard bodies of rock has not been removed; in early maturity considerable portions of their surroundings still remain about them; but in late maturity or early old age the outcropping masses of hard rock have been more perfectly isolated, and are most con-

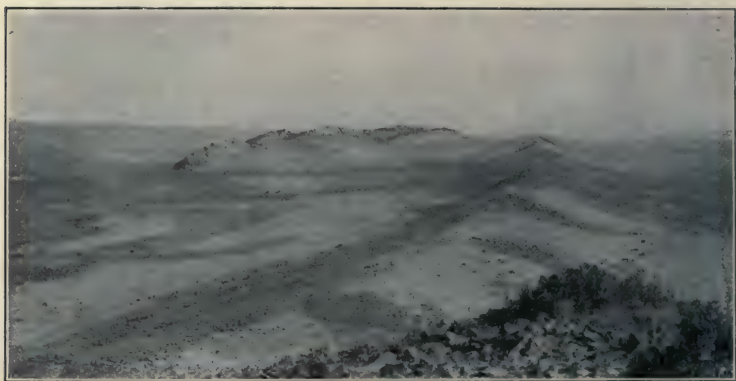


Fig. 120.—Hogbacks; Sec. 22, T. 16, N., R. 112 W., Wyoming. The rock which occasions the hogbacks is the Lazeart sandstone at the base of the Adaville formation. (Veatch, U. S. Geol. Surv.)

spicuous. Most of the even-crested ridges of the Appalachian system, as well as many others which might be mentioned, became ridges in this way. In the final stages of an erosion cycle, the ridges of hard rock are themselves brought low. Isolated remnants of hard rock which remain distinctly above their surroundings in the late stages of an erosion cycle (Fig. 121) are known as *monadnocks*, the name being derived from Mount Monadnock, N. H., an elevation of this sort developed in a cycle antedating the present.

Adjustment of streams to rock structures. Valleys (gullies) are located at the outset without immediate regard to the hardness

and softness of their beds. It is primarily the slope about the head of a gully which determines its line of growth, and, once established, streams tend to hold their courses. The streams on the weaker rock will deepen their valleys more rapidly than others, and those which flow across stronger and weaker rocks alternately, will

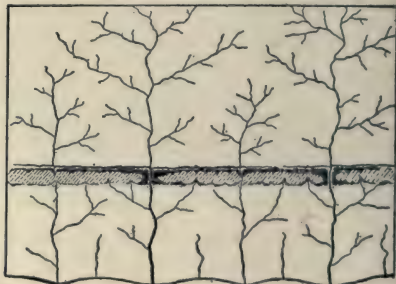
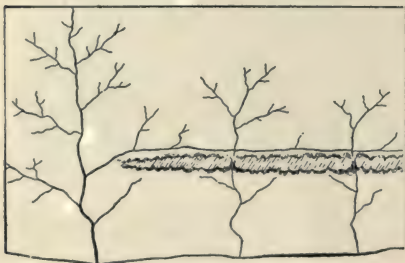
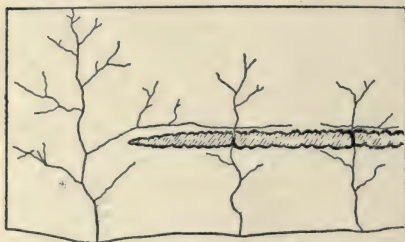
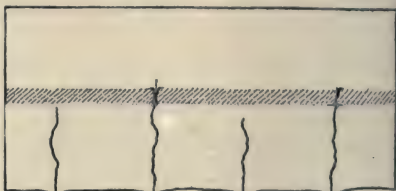


Fig. 121.— A monadnock; a mass of igneous rock isolated by erosion, and remaining high because of its superior hardness. Matteo Tepee, Wyo. (Detroit Photo. Co.)

deepen their valleys more rapidly than those which run on hard rock all the time.

The streams on the weaker rocks, therefore, have an advantage over the others. Being deeper, their tributaries may be lengthened until their heads reach the other valleys, with the results shown in Figs. 122–124. Even where several streams cross the same resistant bed, piracy is likely to take place among them, for some are sure to deepen their valleys faster than others, because of inequalities of volume, load, or hardness. This is illustrated by Figs. 125–127. An actual case is shown in Figs. 87 and 88. Though piracy may take place where streams do not flow over rock of unequal resistance,

it is much more common where they do, for unequal resistance puts one stream at a disadvantage as compared with another.



Figs. 122-124

Figs. 125-127

Figs. 122-124.— Diagrams illustrating piracy, where the stream which does not flow over rock of superior hardness captures those which do. Fig. 123 represents a further development of the drainage shown in Fig. 122, and Fig. 124 represents a still later stage.

Figs. 125-127.— Diagrams to illustrate piracy where the competing streams all cross a hard layer. The diagrams represent successive stages of development.

The changes in the courses of streams, by means of which they come to sustain definite and stable relations to the rock structure beneath, are known as processes of *adjustment*.¹ Since streams and valleys adjust themselves to other conditions as well, this

¹ See Campbell, Jour. Geol., Vol. IV, pp. 567, 657.

phase of adjustment may be called *structural adjustment*. Structural adjustment is not uncommon among rivers flowing over strata

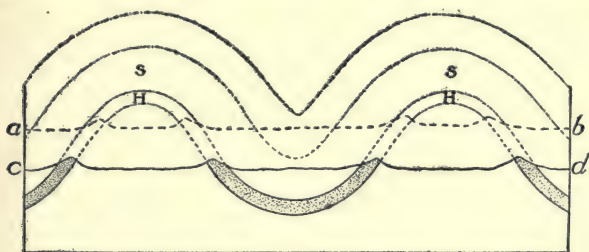


Fig. 128.—Diagram showing the outcrops of hard layers (shaded) on the flanks of truncated folds: *cd*, present surface; *ab*, an earlier erosion surface.

which are vertical or highly inclined, since in these positions the hard and soft strata are most likely to come to the surface in frequent alternation.

The processes of adjustment go on until the streams flow as much as possible on the weaker beds, and as little as possible on the stronger, when adjustment is complete. This amounts to the same thing as saying that the outcrops of the hard layers tend to become divides. In many cases an area is so situated that there is no escape for its drainage except across resistant rock. In this case its drainage is completely adjusted when as few streams as possible cross the resistant rock, and these by the shortest routes.

Adjustment has been carried to a high degree of perfection in most parts of the Appalachian system. Here, as in all other mountains of similar structure, strata of unequal hardness were folded into ridges. The folds were then truncated by erosion,

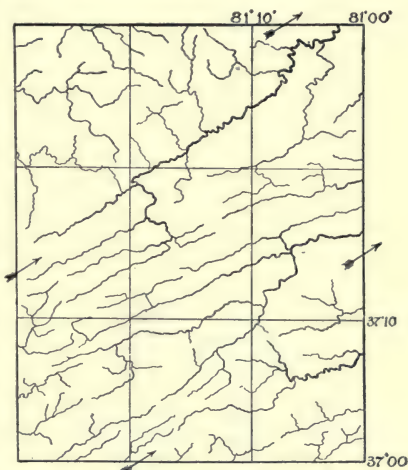


Fig. 129.—Adjusted drainage in a region of folded rocks.

exposing the more and the less resistant beds (*H* and *S*, Fig. 128, respectively) in alternate belts along the flanks of the truncated folds (truncated at *ab* and *cd*). The streams, especially the lesser ones, now flow along the strike of the weaker beds much more commonly than elsewhere, and where they cross the hard layers it is usually at right angles to the strike. This is shown in Fig. 129, where the arrows indicate the direction of strike.

As base-level is approached, the outcrops of hard rock are brought low. When they have been reduced to the level of their surroundings, the streams may flow without regard to the resistance of the rock beneath, for the downward cutting has ceased.

It sometimes happens that rocks of unequal resistance are covered by beds of uniform hardness. A consequent stream

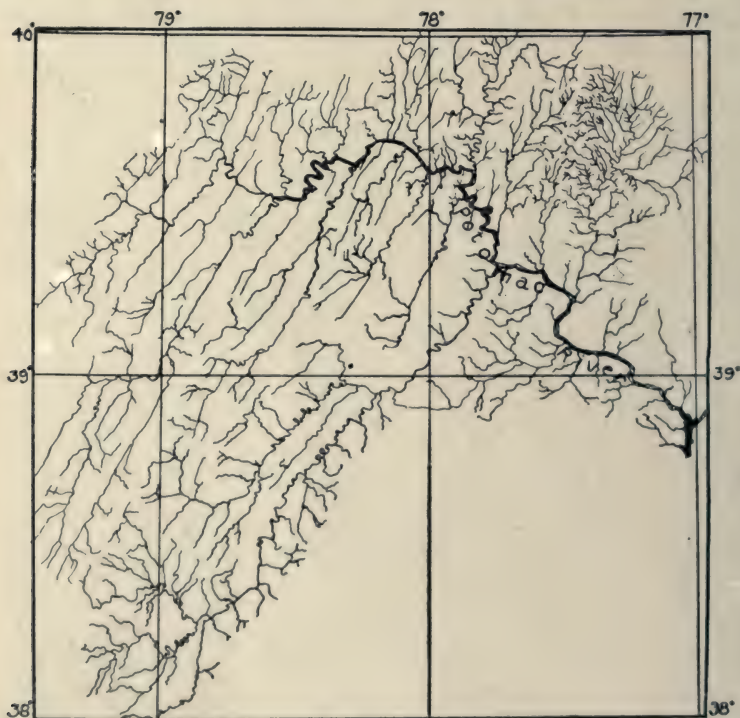


Fig. 129 A.—Streams of the upper Potomac basin, illustrating adjustment. The northeast course of many of the streams is with the strike.

(p. 116) developed on the latter may find itself out of structural adjustment when it has cut its channel down to the level of the heterogeneous beds below. Such a stream is said to be *superimposed* (Fig. 130) on the underlying structure. Structural adjustment is likely to follow in time.

Influence of joints. It has been pointed out that joint planes have somewhat the same influence upon erosion, that bedding planes have when beds are tilted at a high angle. Most rocks are affected by joints, and joints are often nearly vertical. Two sets are generally present, and sometimes more. When there are but two, they usually meet at a large angle (Fig. 2). These joints allow the ingress of water, roots, etc., which help to weather and disrupt rocks. Their effect on erosion may often be seen along a stream which flows in a rock gorge. In such situations, the outlines of

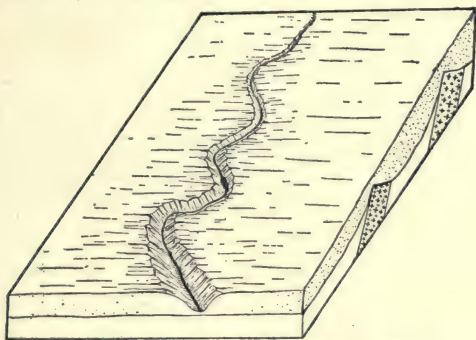


Fig. 130.— Diagram to illustrate superimposition. The consequent stream on the upper formation was superimposed on the underlying structures when the upper bed had been cut through.

the banks are sometimes angular, and sometimes crenate (Fig. 131), the re-entrants being located at the joints. By working into and widening joints, running water sometimes isolates masses of rock as islands (Fig. 132).

In a region free from mantle rock, or where the mantle rock is meagre, joints often determine the courses of valleys by directing the course of surface drainage. This is shown in many parts of the arid West. In regions where the rocks are notably faulted, the courses of the streams are in many cases controlled by the courses of the fault planes.

The jointing of rocks often shows itself distinctly in the weathered faces of cliffs (Fig. 133), especially in arid and semi-arid regions, or where the slope is too steep for the accumulation of soil and rock-waste on its surface.

Joints in rocks may occasion the development of natural bridges.



Fig. 131.— Figure showing crenate river bank, the re-entrants being determined by joints. Dells of the Wisconsin River, near Kilbourn, Wis. (Atwood.)



Fig. 132.— An island formed by river erosion in jointed rock; Lower Dells of the Wisconsin. (Atwood.)

If above a waterfall, for example, there were an open joint in the bed of the stream (as at *b*, Fig. 134), some portion of the water would descend through it. After reaching a lower level it might



Fig. 133.— Effect of columnar structure on weathering. Material but partially consolidated. Spur of south end of Sheep Mountain. (Lippincott, U. S. Geol. Surv.)

find or make a passage through the rock to the river at the falls. If even a little water took such a course, the flow would enlarge the passageway through the joint to the valley at the falls (*bcde*, Fig. 134). This passageway might in time become large enough to accommodate all the water of the river. In this case, the entire fall would be transferred from the position which it previously

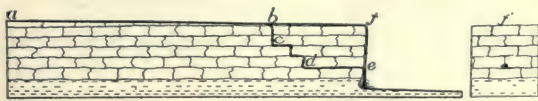


Fig. 134.— Diagram to illustrate the initial stage in the development of a natural bridge. Longitudinal section at the left, cross-section at the right.

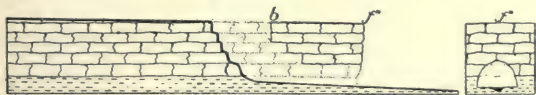


Fig. 135.— A stage later than that shown in Fig. 134.

occupied (*f*) to the position of the enlarged joint (*b*). The falls would then recede. The underground channel between the old

falls and the new would then be bridged by rock (bf'' and f''' , Fig. 135). The natural bridge near Lexington, Va., (Fig. 136), almost 200 feet above the stream which flows beneath it, is believed to have been developed in this way; but it is not to be understood that all natural bridges have had this history.

Folds. The erosion of folded strata (anticlines and synclines) leads to the development of distinctive topographic features. So



Fig. 136.— The Natural Bridge of Virginia. (U. S. Geol. Surv.)

soon as a fold begins to be lifted, it is, by reason of its position, subject to more rapid erosion than its surroundings. For the same reason, the crest of the fold is likely to be degraded more rapidly than its lower slopes, and must suffer more degradation before it is brought to base-level. Folds are usually composed of beds of unequal resistance, and as the degradation of a fold proceeds, successive layers are worn from the top, and the alternating hard and soft layers composing it are exposed. When this is accomplished, adjustment of the streams is likely to begin, and

the water-courses, and later the valley plains, come to be located on the outcrops of the less resistant layers, while the outcrops of the stronger beds become ridges.

If the axis of an eroded anticline were horizontal, a given hard layer, the arch of which has been cut off, would, after erosion, outcrop on both sides of the axis. When the topography had become mature, these outcrops would constitute parallel ridges, or parallel lines of hills; when the region had been base-leveled, the outcrops would be in parallel belts, though no longer ridges or hills. The

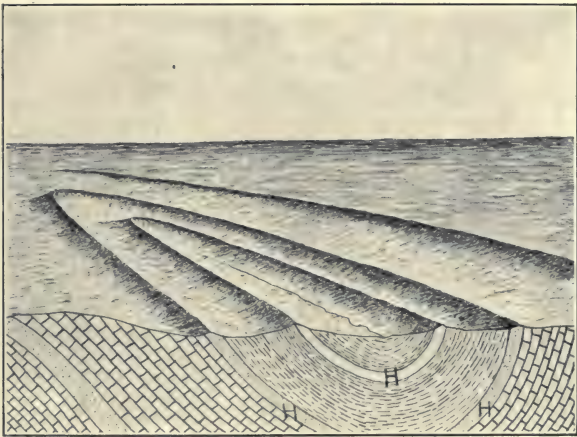


Fig. 137.— A canoe-shaped valley bordered by a ridge formed by the outcrop of a hard layer in a plunging syncline. The ridge bounding the canoe-valley is separated from an outer ridge by a curved valley, underlain by relatively weak rock. (Willis.)

lower the plane of truncation, the farther apart the outcrops would be in the anticline, and the nearer together in the syncline (compare outcrop of H, along *ab* and *cd*, Fig. 128).

If, on the other hand, the axis of the anticline or syncline is not horizontal, that is, if it *plunges* (dips), the topographic result will be different. In this case the outcrops of a given layer on opposite sides of an anticline would converge in the direction of plunge, and come together at the end. At a stage of erosion antedating planation (say late maturity) there would be a ridge or a succession of hills, in the position corresponding to the outcrop of a hard layer,

with a canoe-shaped valley within. If two hard layers were involved, instead of one, there would be two encircling ridges, with a curved valley between them, and a canoe-shaped valley within the innermost (Fig. 137). A succession of plunging anticlines



Fig. 138.—Cross-section of a portion of the Appalachian Mountains to illustrate the phenomena of erosion cycles. (Rogers.)

and synclines might give rise to a very complex series of ridges and valleys. Illustrations of the above phenomena are found at various points in the Appalachian Mountains.¹

In the structural adjustment which goes with the erosion of folds, it often happens that the valleys come to be located on the anticlines, after they have been worn down, while the outcrops of the hard layers on the flanks of the anticlines, or even in the original synclines, become the mountains (Fig. 138).

EFFECT OF CHANGES OF LEVEL

Rise. If, after being base-leveled, or notably reduced by erosion, a region is uplifted so as to increase the gradients and velocities of its streams, they are said to be *rejuvenated*, and a new cycle of erosion is begun. The renewed youth differs from the first youth, in that the streams are already in existence in well defined channels. The rejuvenated streams erode their valleys after the manner of youthful streams. They excavate new valleys in the bottoms of older ones (Figs. 139 and 140), deepening them, or tending to, until they reach the new grade plane.

The new valley in the old one may be developing all along its course at the same time, or it may begin at the debouchure of a stream and work headward. In either case, the tributaries are rejuvenated when their main is lowered at the point of union.

Another evidence of rejuvenation is found in entrenched mean-

¹ See Willis, The Northern Appalachians, in *Physiography of the United States*.

ders. If an old winding stream is rejuvenated, the deepened channel follows the course of the stream before rejuvenation. The result is that a new winding gorge is cut; that is, the old meanders are *entrenched*. Entrenched meanders are rather common in the Appalachian Mountains (Pl. XI), and are known in other parts of the world.¹ Entrenched meanders and new valleys in the bottoms of old ones are among the commoner marks of rejuvenation. With rejuvena-

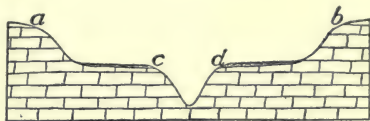


Fig. 139.—Cross-section of a wide valley, *ab*, in the bottom of which a younger valley, *cd*, has been excavated, as the result of uplift.

tion of the drainage, a new cycle of erosion is begun, whether the preceding one was complete or not.

The recognition of different cycles of erosion, separated by uplifts, is often easy. The principles involved are illustrated by Fig. 141, which represents an ideal profile of considerable length (say 20 miles). The points *a*, *a'*, and *a''* have about the same elevation. Below them there are areas *b*, *b'*, and *b''*, which have a nearly common elevation, below which are the sharp valleys *d*, *d'*, and *d''*. The points *a*, *a'*, and *a''* represent the cross-sections of ridges formed by the outcrops of layers of hard rock. If the crests of the ridges are level, the points *a*, *a'*, and *a''* must represent remnants of an old base-level, *since at no time after a ridge of hard*



Fig. 140.—Diagram to illustrate an ideal case of rejuvenation as the result of uplift. The black area at the bottom represents the sea.

nants of an old base-level, *since at no time after a ridge of hard*

¹ Davis. The Seine, the Meuse and the Moselle. Nat. Geog. Mag., Vol. VII, pp. 181–202, and 228–238; an article which throws much light on the behavior of rivers.

rock becomes deeply notched does it acquire an even crest, until it is base-levelled.¹ After the cycle represented by the remnants *a*, *a'*, and *a''* was completed, the region suffered uplift. A new cycle represented by the plain *b*, *b'*, and *b''* was well advanced, though not completed, when the region was again elevated, and the rejuvenated streams began to cut their valleys *d*, *d'*, and *d''* in the plain of the previous incomplete cycle. The elevations, *c* and *c'* (intermediate in elevation between *a*, *a'*, and *a''*, and *b*, *b'*, and *b''*), may represent either remnants of the first base-level plain, lowered, but not obliterated, while the plain *b*, *b'*, *b''* was developing; or



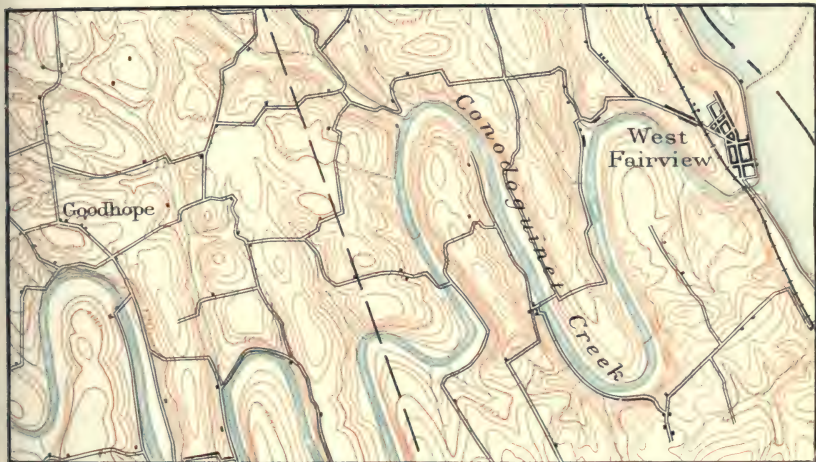
Fig. 141.—Diagram to illustrate cycles of erosion where the beds are tilted

they may represent a cycle intermediate between that during which *a*, *a'*, *a''* and *b*, *b'*, *b''* were developed.

If the strata involved are horizontal, the determination of cycles is sometimes less easy. Thus in Fig. 142, it is not possible to say whether *a* and *a'* represent remnants of an old base-level, or whether they represent the original surface from which degradation started. So, too, the various benches below *a*, such as *b*, *b'*, and *b''*, may readily be the result of the superior hardness of beds at this level. For the determination of successive cycles in the field, it is necessary to consider areas of considerable size, and to eliminate the topographic effects of inequalities of hardness.

It is by the application of the preceding principles that it is known that the Appalachian Mountains, after being folded, were reduced to a peneplain (the Kittatinny peneplain) from the Hudson River to Alabama. The old peneplain surface is indicated by the level crests of the Appalachian ridges. The system was then warped (not folded) up, and in the cycle of erosion which followed, broad plains were developed at a new and lower level, corresponding in a general way to the plains *b*, *b'*, and *b''* of Fig.

¹ Other views have been entertained. See Tarr, *Am. Geol.*, Vol. XXI, pp. 351-370, and Daly, *Jour. of Geol.*, Vol. XIII, pp. 105-125.



Entrenched meanders. Scale, about 1 mile per inch. (Harrisburg, Pa., Sheet.
U. S. Geol Surv.)

PLATE XII



A Section of the California Coast, showing lands near the coast, which have recently emerged. Scale, about 1 mile per inch. (Oceanside, Cal., Sheet. U. S. Geol. Surv.)

141. The plains were located, for the most part, where the less resistant strata come to the surface. Above them rise even-crested ridges, the outcrops of the resistant layers, isolated by the degradation of the weaker beds between. It is the outcrops of these layers which constitute many of the present mountain ridges (the high points of Fig 141). The evenness of their crests testifies to the completeness of the first peneplanation. The evenness of the crests is, however, interrupted by (1) notches cut by the streams in later cycles, and (2) by occasional elevations (monadnocks) above the common level. The monadnocks are generally rather



Fig. 142.— Diagram to illustrate cycles of erosion where the beds are horizontal.

inconspicuous, but there is a notable group of them in North Carolina and Tennessee, of which Mount Mitchell and Roan Mountain are examples. When long distances are considered, the ridge crests depart somewhat from horizontality. This is believed to be due, in part at least, to deformation of the old peneplain during the uplift which inaugurated the second cycle of erosion.

The extent to which the second cycle of erosion recorded in the present topography had proceeded before its interruption by upwarp, is indicated by the extent of the valley plains (Fig. 141) below the mountain ridges. While these plains were being developed on the weak rocks, narrow valleys only were cut in the resistant rocks which stood out as ridges. Deep narrows of this sort are often called *water-gaps*. Similar valleys, whether shallow or deep, from which drainage has been diverted, are sometimes called *wind-gaps*.

The second cycle of erosion, while still far from complete, was interrupted by uplift (relative or absolute), and a new cycle inaugurated. This event was so recent that the new (third) cycle has not yet advanced far.

Some of the features just described are illustrated by Fig. 118. The even mountain crest in the background is the Kittatinny

Mountain of New Jersey and its continuation in Pennsylvania. In common with other corresponding crests, it is a remnant of the oldest recorded base-level (or peneplain) of the region. The great

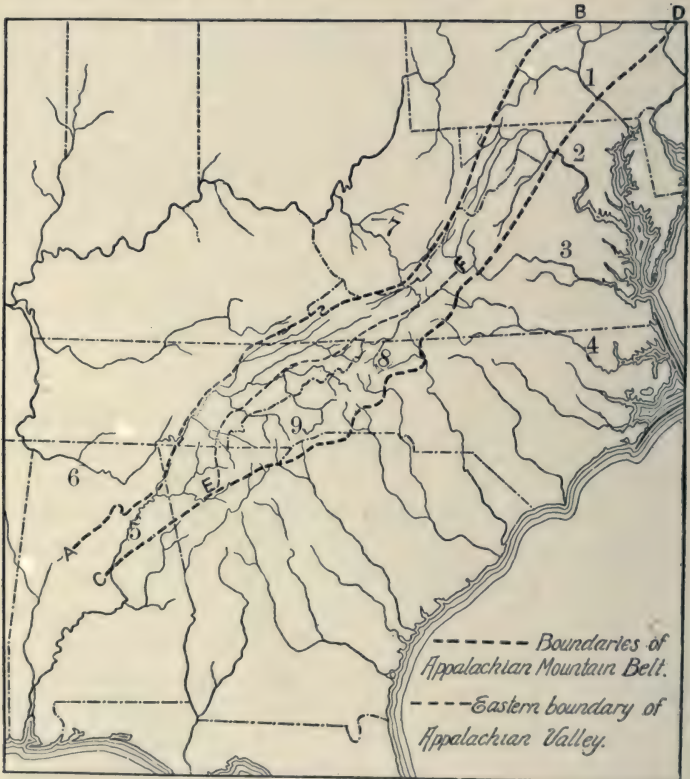


Fig. 143.— Showing certain peculiarities of Appalachian drainage. 1 = the Susquehanna; 2 = the Potomac; 3 = the James; 4 = the Roanoke; 5 = the Coosa; 6 = the Tennessee; 7 = the Kanawha; 8 = head of New River; 9 = head of the French Broad.

gap in the mountain is the Delaware Water-Gap. Below the mountain crest there is another plain, developed in a subsequent cycle of erosion, while the valley plain in the foreground represents the work of a still later cycle.

Many of the peculiarities of the drainage of the Appalachian

Mountain system are intimately connected with the history just outlined. Thus three great rivers, the Delaware, the Susquehanna, and the Potomac, have their sources west of the Appalachians proper, cross the system in apparent disregard of the structure, and flow into the Atlantic. The James and Roanoke head far to the west, although not beyond the mountain system, and flow eastward, while the New River (leading to the Kanawha) farther south, heads east of the mountain-folds, and flows northwestward across the alternating hard and soft beds of the whole Appalachian system, to the Ohio (Fig. 143). The French Broad, a tributary to the Tennessee, has a similar course. Such streams are clearly not in structural adjustment, and afford good opportunities for piracy. Their courses were apparently assumed during the time of the Kittatinny base-level, when the streams had so low a gradient as not to be affected by the structure. Elevation rejuvenated them, and they have held their courses in succeeding cycles across beds of unequal resistance, though smaller streams have become somewhat thoroughly adjusted. Crustal deformations have also helped them to hold their courses, for the Cretaceous peneplain seems to have been tilted to the southeast at its northern end, and to the southwest at its southern, when the succeeding cycle began.

Streams which hold their early courses in spite of changes which have taken place since their courses were assumed are said to be *antecedent*. They antedate the crustal movements which, but for pre-existent streams, would have given origin to a different arrangement of river courses. As a result of crustal movements, therefore, a consequent stream may become antecedent. Master streams are more likely to hold their courses, and therefore to become antecedent, than subordinate ones.

The uplift of base-leveled beds, especially if the beds are tilted so as to bring layers of unequal resistance to the surface at frequent intervals, affords conditions favorable for extensive adjustment. The numerous wind-gaps in the mountain ridges, representing the abandoned courses of minor streams, and the less numerous water-gaps, which indicate the resistance of large streams to structural adjustment, are instructive witnesses of the extent to which adjustment has gone. So extensive has been the adjustment among

the streams of the Appalachian Mountains that there is probably no considerable stream in the whole system which has not gained or lost through its own or its neighbor's piracy.

Sinking. The land on which a river system is developed may be depressed relative to sea-level. In this case the sea occupies



Fig. 144

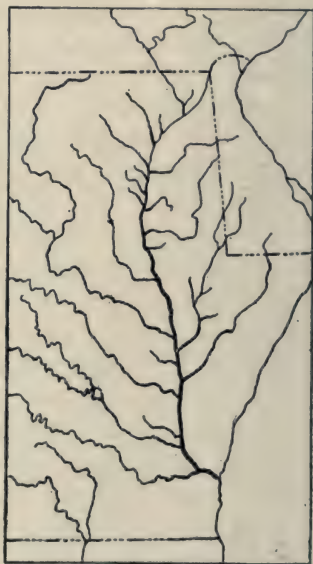


Fig. 145

Fig. 144.—Chesapeake Bay and its surroundings. The bay is a drowned river valley, and the lower ends of its tributary valleys are also drowned.
 Fig. 145.—The drainage of the region about Chesapeake Bay as it would have been but for drowning.

the lower ends of valleys, converting them into bays and estuaries. A valley in this condition is said to be *drowned*. Of drowned valleys there are many examples along the Atlantic coast. Thus the St. Lawrence is drowned up to Montreal, and the Hudson up to Albany. If the drowned portion of the latter valley were not so narrow, it would be a bay. Delaware and Chesapeake bays, as well as many smaller ones, both north and south, are likewise the drowned ends of river valleys (Figs. 144 and 145).

Successive rising and sinking. Another peculiarity of valleys and streams resulting from changes of level is illustrated by Pl. XII. The main valleys of this part of the coast were developed when the land stood higher than now. Later, the subsidence of the coast converted the lower ends of the valleys into bays or fiords. The bays were then transformed into lakes by deposition at their mouths. Subsequent rise of the land or depression of the sea allowed the drainage from the old lagoons to cut across the deposits which had converted the bays into lagoons. The result is an older, wider valley above, succeeded by a younger one near the debouchure.

Differential movement. Warping. A land surface on which a river system is established may suffer warping, some parts going up and others down. Above an upwarp which notably checks its flow, a stream is *ponded*. If a stream holds its course across a notable uplift athwart its valley, it becomes an antecedent stream. The Columbia River has been thought to hold its antecedent course across areas which have been uplifted (differentially) hundreds and even thousands of feet¹. Some of the striking scenic features of this noble valley are the result of these changes in the country through which it flows. A lesser stream would have been diverted, as many of its tributaries have been. Even its course across the Cascade Range has been interpreted as antecedent.

THE AGGRADATIONAL WORK OF RUNNING WATER

We have seen that rivers carry mud, sand, gravel, etc., from land to sea, and that their goal is the degradation of the land nearly to the level of the sea. We have also seen that rivers do not always carry the sediment derived from the land directly to the sea. It is often dropped for a time on the land, perhaps to be picked up and carried on again when the conditions for its transportation are more favorable. We have now to inquire more particularly into the causes and especially the results of deposition.

Causes of Deposition

When running water drops its load, or any part of it, it is generally because the current has lost something of its velocity. We

¹ Russell. Rivers of North America, p. 279.

have already seen that gradient and volume are the most important factors in determining the velocity of a small stream.

1. **Loss of velocity.** The commonest cause of loss of velocity is decrease of gradient. Running water may lose velocity (1) suddenly, as when it passes from a steep slope, whether of hill or mountain, to a gentle one, or to a body of standing water; or (2) slowly, as in descending a valley the gradient of which becomes gradually less. We therefore look to the places where these changes in velocity occur for the principal deposits of running water.



Fig. 146.— Delta of Lake St. Clair. (Lake Survey Chart.)

Streams also become slower wherever their channels become wider, even if volumes and gradients remain constant.

Decrease of volume is a less common cause of decrease of velocity. Streams generally increase in size with increasing distance from their sources, but to this general rule there are exceptions. (1) If a stream flows through a very dry region, it may receive few tributaries and few springs, while evaporation is great and the thirsty soil and rock through which it flows absorb some of the water. In a dry region, therefore, a stream may diminish as it flows, and may even disappear altogether (Pls. II and XIII). (2) A stream sometimes breaks up into several streams (Fig. 146). The volume of

each is less than that of the original stream. (3) Still again, many streams, especially in arid regions, have much of their water withdrawn for purposes of irrigation. Many streams in the west are made smaller in this way. (4) Streams decrease in volume as their floods decline, and so deposit in their channels during low water, where they eroded during high water.

Location of Alluvial Deposits and their Topographic Forms

1. **At the bases of steep slopes.** Every shower washes fine sediment down the slopes of the hills, and much of it is left at their



Fig. 147 — An alluvial cone. (U. S. Geol. Surv.)

bases. Its lodgment is sometimes shown by the fact that fences in such situations are in places buried by the mud lodged against them. Temporary streams, bred of showers, sometimes flow down steep slopes, and are suddenly checked at their bases. Such streams gather much debris from the steep slopes, but abandon it where their velocity is suddenly checked. Thus, at the lower end of the new-made gully on the hillside there is commonly a mass of debris which was washed out of the gully itself (Figs. 72 and 147). Material in such positions accumulates in the form of a partial cone, known as an *alluvial cone*. Alluvial cones have much in common with cones of talus; but in the latter, gravity brings the material down without the aid of water, or with but little help from it. Be-

tween talus cones and alluvial cones there are, however, all gradations.

Conspicuous alluvial cones are common at the bases of steep slopes in semi-arid regions; for in such regions the rainfall is fitful, and the occasional heavy showers, which give rise to temporary and powerful torrents, favor the development of cones of great size. At the bases of the mountain ranges in the Great Basin,



Fig. 148.—Valley showing deposition at the bases of valley slopes, tending to give the valley a U-shaped base. Unaweep Canyon, Colorado. (Cross, U. S. Geol. Surv.)

the talus and alluvial cones from the mountains are sometimes 2,000 or 3,000 feet high.

An *alluvial fan* is the same as an alluvial cone, except that it has a lower angle of slope. The term *fan* is indeed more appropriate than *cone* for most alluvial accumulations at the bases of slopes. The lower angle of the fan may be due to the less abrupt change of slope where it is developed, to the larger quantity of water concerned in its deposition, to the smaller amount of detritus, or to its greater fineness. Less change of slope, more water, and less and finer material, all favor the wider distribution of the sediment, and so the development of fans rather than cones. Nearly all young rivers descending from mountains build fans where they leave the mountains. Thus, the rivers descending from the Sierras to the great valley of California build great fans at the base of the

range. Most of the rivers descending from the Rockies to the plains to the east have done the same thing. The fans of streams descending from the mountains are often many miles across. The fan of the Merced River in California, for example, has a radius of about 40 miles.

The fans made by neighboring streams may grow laterally until they merge. The union of several such fans makes a *compound alluvial fan*, or a *piedmont alluvial plain* (Pl. XIII). Such plains exist at the bases of most considerable mountain ranges, and sheet wash, as well as streams, contribute to them. The depth of alluvial

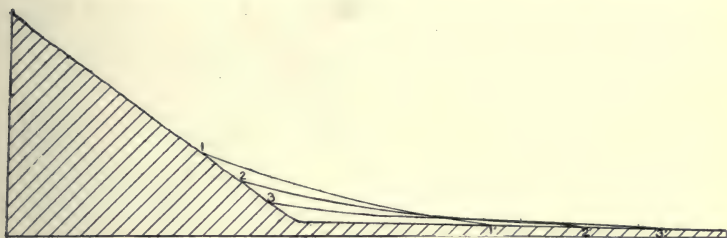


Fig. 149.—Diagram to illustrate the spreading of alluvial deposits in a piedmont position. The deposits may first take the position represented by the line 1-1'. At a later stage, they take the position represented by the line 2-2', being spread farther from the mountain and having a lower surface slope. At a still later time, they take the position 3-3', with a still lower slope and a still wider spread.

material in such plains is often scores and sometimes hundreds of feet. One of the most remarkable features of these land deposits is their great spread. Thus east of the Rocky Mountains they extend out more than a hundred miles in some places. This wide spread appears to be the result of the long-continued action of running water. The alluvial cone or steep fan, as first built, is degraded later, and its materials spread more widely. As the gradient of the running water which makes the fan becomes lower, the higher parts of the fan are spread out farther and farther, with continually lower gradient, as suggested by Fig. 149.

Deposits of this sort have probably been far more important in the past than has been generally recognized. Much of the material of the Coastal Plain of the Atlantic and Gulf slopes of the United

States appears to have been deposited in this way. A large part of the Great Plains is covered with wash from the Rocky Mountains, and similar deposits are of great extent and depth east of the Andes and south of the Himalayas. They are, indeed, of significant extent and depth about almost every mountain range which has been carefully studied, especially where plains are adjacent to the mountains. It seems clear that similar deposits must have

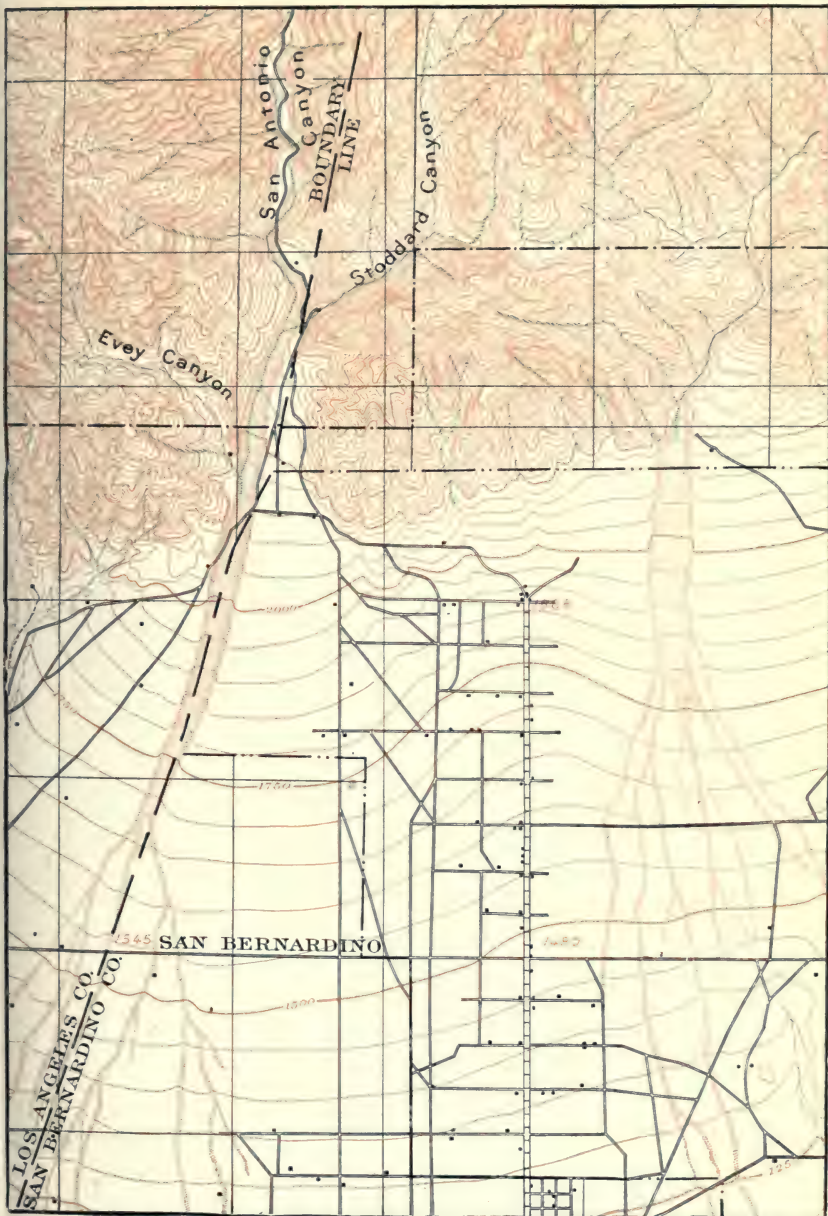


Fig. 150—A branching stream. Junction of the Cooper and Yukon rivers, Alaska. Shows also bars, etc. (U. S. Geol. Surv.)

been made at all stages in the past history of the earth, whenever and wherever mountainous lands bordered plains.

Formations of this general sort, made at the bases of high lands, have now been recognized among the ancient formations of the earth, as well as among the recent ones, and some of the ancient beds of sediment deposited in this way, attained thicknesses of hundreds and even thousands of feet. They probably attained their greatest thickness, as now, in basins.

2. **In valley bottoms.** A stream which makes deposits in its channel reduces the size of the channel. In time it may become too small to hold all the water. A part then breaks out, and follows a new course over the valley flat. This process may be repeated again and again (Fig. 150). Streams sometimes deposit bars in their channels, especially in low water. The bars may be



A piedmont alluvial plain or compound alluvial fan in Southern California.
 Scale about 1 mile per inch. (Cucamonga, Cal., Sheet, U. S. Geol. Surv.)

PLATE XIV



Stream flats. The Missouri and Big Sioux Rivers. Scale, about 2 miles per inch. (Elk Point, S. Dak.—Ia.—Neb. Sheet, U. S. Geol. Surv.)

swept away in time of flood, but they sometimes become more or less permanent islands.

The profiles of most valleys are curves, the curvature becoming less as the lower end of the stream is approached (Fig. 151). It

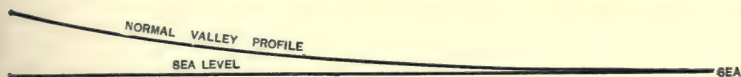


Fig. 151.— Profile of a normal valley.

therefore happens that as a stream descends its valley it generally reaches a point where its reduced gradient so diminishes its velocity that it must abandon some of its load. In this way sediment is distributed for long distances along valley bottoms. It is left in

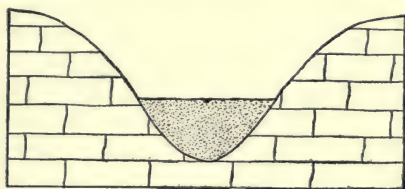


Fig. 152.— Flat developed by aggradation — diagrammatic.

the channels of streams in low water, and spread over their flood plains in high water, aggrading them and making them *alluvial plains*. Deposition in a valley which has no flat tends to develop one (Fig. 152). Alluvial deposits on valley flats are usually but



Fig. 153.— Levees of the Mississippi in cross-section, four miles north of Donaldsonville, La. Vertical scale $\times 50$. The horizontal line represents sea-level. The bottom of the channel is far below sea-level at this point.

a few feet, or at most a few scores of feet thick; but in some cases they reach hundreds of feet.

Natural levees (Fig. 153) are developed in flood plains aggraded by occasional floods. At such times the current in the main channel is swift; but as the water escapes its channel and spreads over

the adjacent flat, its velocity is checked promptly, because its depth suddenly becomes less. It must therefore abandon much of its load then and there. Repeated deposition in this position, in excess of that over other parts of the flood plain, gives rise to the levees.

Scour-and-fill. Aggrading streams deepen their channels periodically to a notable extent, and the deepening of the channel takes

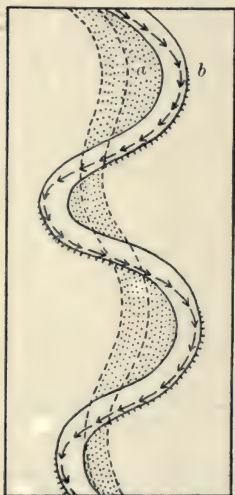


Fig. 154

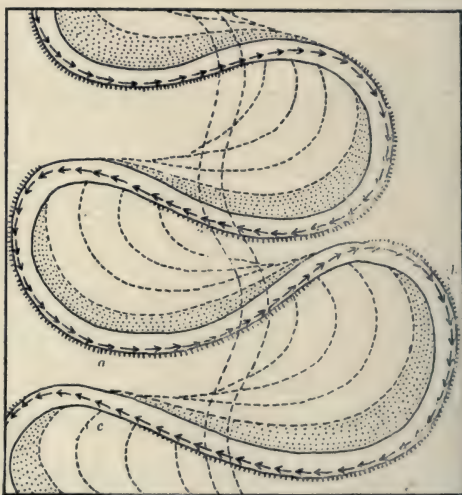


Fig. 155

Fig. 154.— Diagram illustrating an early stage in the development of river meanders. The dotted area represents the area over which the stream has worked.

Fig. 155.— A later stage in the development of meanders.

place at the very time when the flood-plain is being aggraded. In other words, the stream in flood aggrades its plain, and degrades its channel. This follows from the fact that the current is slow in the former position, where the water is shallow, and rapid in the latter, where it is deep. After the flood subsides, the channel, deepened while the current was torrential, is filled up again by sediment from the feebler current. This alternate deepening and filling is known as *scour-and-fill*. It is well illustrated by the Missouri River. At Nebraska City, scour reaches depths of 70 to 90 feet

occasionally.¹ At Blair, about 25 miles above Omaha, the same river is believed to cut to bed-rock (about 40 feet below the bottom of the channel in low water) during floods.² All streams similarly situated do a like work. The material thus eroded is shifted down-

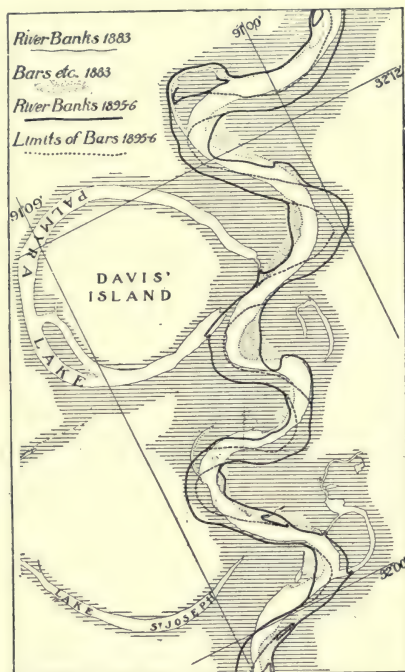


Fig. 156.— Meanders and cut-offs in the Mississippi Valley below Vicksburg. The figure shows the migration of the meanders down stream, and their tendency to increase.

stream, some of it for short distances only, and some of it to the sea. Even an aggrading stream therefore is not without erosive activity; it is a stream whose fill exceeds its scour, not one which has ceased to erode.

Materials of the flood-plain. As a result of its varying velocities in flood and low water, a stream may deposit coarse material at

¹Cooley. Rept. U. S. Engineers for 1879-80, Pt. II, pp. 1060 and 1071.

²Gerber. Cited by Todd. Bull. 158, U. S. Geol. Surv., pp. 150, 151.



Fig. 157.— Delta of the Mississippi. The dotted line outside the land represents the 3-fathom line.

one time and fine at another. Flood-plain deposits are often, therefore, very heterogeneous, ranging from the finest mud, through sand, to gravel, and even boulders. In general they become finer down-stream. In a given plain, they are usually coarser at the bottom, and finer toward the top.

Flood-plain meanders. A stream with an alluvial plain is likely to meander widely (Pls. XIV and VIII). In general terms this may be said to be the result of low velocity, which allows the stream to be turned aside easily. Were the course of such a stream made straight, it would soon become crooked again. The manner



Fig. 158.— A delta in a lake. The village is Silva Plana, in the Engadine, Switzerland. (Robin.)

of change is illustrated by Figs. 154 and 155. If the banks are less resistant at some points than at others, as is always the case, the stream will cut in at those points. If the configuration of the channel is such as to direct a current against a given point, *b* (Fig. 154), the result is the same, even without inequality of material. Once a curve in the bank is started, it is increased by the current which is directed into it. Furthermore, as the current issues from the curve, it impinges against the opposite bank and develops a curve at that point. The water issuing from this curve develops another, and so on.

Once started, the curves or meanders tend to become more and more pronounced (Fig. 155). In the case represented by Fig. 1, Pl. VIII, the narrow neck of land between curves is almost

cut through. A later stage in the process is shown in Fig. 2, Pl. VIII.

When the stream has cut off a meander, the abandoned part of the channel often remains unfilled with sediment. If it contains standing water, as it often does, it becomes the site of a lake (Fig. 156). Such lakes sometimes have the form of an ox-bow, and so are called *ox-bow lakes* (Pls. XIV and VIII).

3. **At debouchures.** Where a swift stream flows into the sea or a lake, its current is promptly checked and soon destroyed alto-

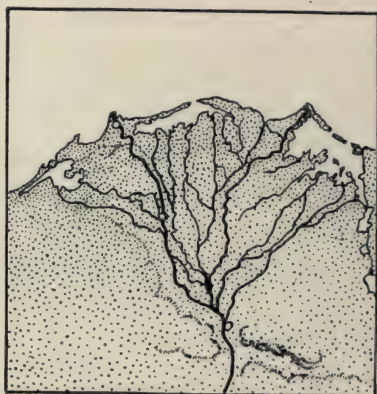


Fig. 159.— The delta of the Nile.

gether. Its load is accordingly dropped. If not washed away by waves, etc., the deposits of river-borne sediment in such places make *deltas* (Figs. 146 and 157 to 159).

The delta has some points in common with the alluvial fan. In both cases the principal deposit is concentrated at the point where the velocity is suddenly checked. In the case of the delta, however, the current is checked more completely, and the debris accumulates (at the outset) below the surface of the standing water. In form, the delta differs from the alluvial fan in that its edge has a steep slope (compare Figs. 160 and 161).

Once a delta is started below water, deposition takes place upon its surface, which may be built up to, and even above, the water-

level. That part of the delta above the surface of the water in which it is built, is like a flat alluvial fan.

Much land has been made by delta-building. Thus the Colorado River has built a great delta many square miles (above water) in area at the head of the Gulf of California (Fig. 162). The delta has been built quite across the gulf near its upper end, shutting off the head. In the arid climate of the region, this shut-off head has become a nearly dry basin, the lowest part of which is about 300 feet below sea-level. The Skagit River, in Washington, has built out its delta so as to surround what were high islands in

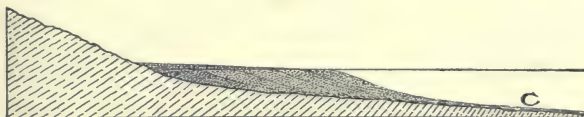


Fig. 160.— Diagrammatic profile and section of a delta.



Fig. 161.— Diagrammatic profile and section of an alluvial fan.

Puget Sound, thus joining them to the mainland. The deltas of the Mississippi (Fig. 157), the Nile and the Hoang-Ho Rivers are among the large and well-known deltas. The united delta of the Ganges and Brahmaputra is also a great one, having an area (above water) of some 50,000 square miles. The Po has built a delta 14 miles beyond the former port of Adria, which gave its name to the Adriatic Sea. The Rhone River (France) has advanced its delta some 15 miles in as many centuries.

The effect of delta-building is to increase the area of the land; but it is to be noted that the processes which lead to delta-building reduce the volume of the land-masses, even though they increase their area.

The outline of some deltas is determined by the surroundings in which they are built. When, for example, a delta is built into a bay, the form of the bay-head determines the shape of the delta.

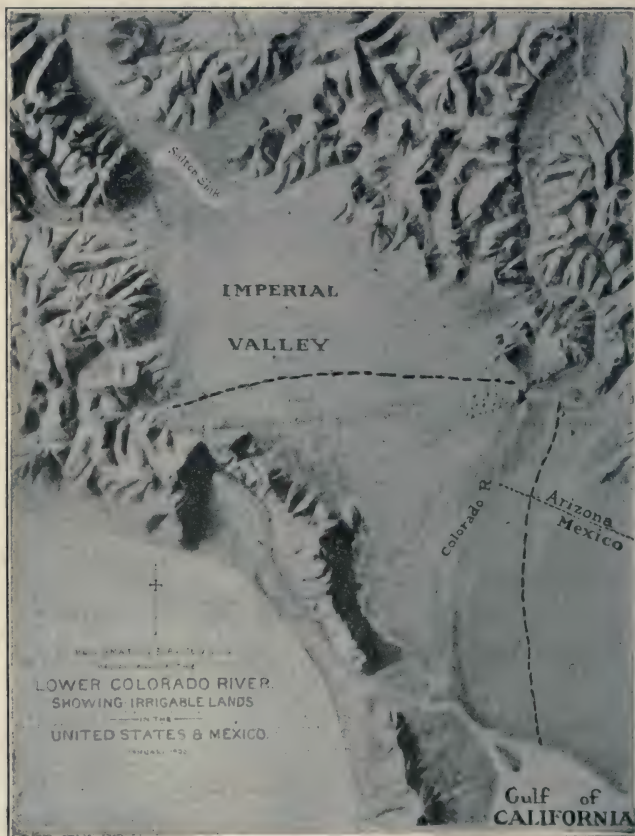


Fig. 162.—Relief-map of an area about the head of the Gulf of California, showing the delta of the Colorado River, outlined, in a general way, by dotted lines. The Salton Sink is shown at the north, and the Imperial Valley lies south of the sink. (U. S. Rec. Serv.)

The normal form of a delta built on an open coast is somewhat semicircular, though there is often a fringe of *delta fingers* which together have some resemblance to the Greek letter Δ , which gave these terminal deposits of streams their names.

STREAM TERRACES

Stream terraces¹ are bench-like flats or narrow plains along the sides of valleys (Fig. 163-4) and above their bottoms. They are usually narrow, but sometimes have great length in the direction of the axis of the valley.

The commoner river terraces are remnants of former flood-plains, below which the streams which made them have cut their channels. They originate in various ways. (1) Some are due to inequalities of hardness (Fig. 117). (2) If an alluvial flood-



Fig. 163.—Terraces on the Fraser River at Lilloet, B. C. (Photo. by Calvin.)

plain has been built as the result of an excessive supply of sediment (p. 183), the exhaustion or withdrawal of the excessive supply would leave the stream again relatively clear, and free to erode where it had been depositing. It would forthwith set to work to carry away the material which it had temporarily unloaded on the plain. The plains built up in many valleys in the northern part

¹For discussions of terraces see Gilbert's *Henry Mountains*, p. 126; Davis' *River Terraces in New England*, *Bull. of the Mus. of Comp. Zool. Geol. Series*, Vol. V, pp. 282-346; and Dodge, *Proc. Boston Soc. of Nat. Hist.*, Vol. XXVI, pp. 257-273.

of our continent during the glacial period, when the drainage from the ice coursed through them, have subsequently been partially destroyed by erosion, and their remnants have become terraces.

(3) A notable increase in the volume of a stream, without corresponding increase in load, as when one stream captures another, may occasion the development of terraces by allowing the enlarged stream to deepen its channel. (4) The uplift of a region in which there are well developed river flats, would rejuvenate the streams, and parts of their old flood-plains would be left as terraces. Other occasional causes which need not be mentioned here, may give rise to terraces.

Apart from the terraces due to the more or less occasional causes mentioned above, terraces are developed in the normal course of every stream's history. The causes are as follows:

(1) The head of the valley-plain where the first notable deposition takes place, normally advances up-stream. After the advance has been considerable, the descending stream may, on reaching the head of its valley-plain, lose so much of its load as to be able to sink its channel into the flood-plain farther down the valley.

(2) Again, so long as a stream is actively eroding at its head, there is likely to be some aggradation below. At a later stage in the stream's history, when erosion at the head has become less because of the reduction of the surface, less material will be carried from the upper part of the valley, and the stream on the flood-plain below, formerly loaded with material from up the valley, is now free to take up and carry away material temporarily left on the flood-plain. The result is a deepening of the channel.

(3) A stream does not drop all its load at the head of its plain, but only its excess; but it will always drop coarse sediment to take fine, if fine is available. For a relatively small amount of coarse material dropped, a relatively large amount of fine may be taken up, both because fine sediment takes less of a stream's energy, pound for pound, than coarse does, and because more of a stream's energy may be utilized in carrying fine material. Other things being equal, it follows that when a stream drops coarse material to take fine, its channel is degraded unless there is at the same time a great reduction in the stream's energy. Such reduction

is likely to go with the decreasing declivity down-stream; but this is partly, or sometimes wholly, counterbalanced by the increasing volume of water. By the exchange of load, therefore, a stream may ultimately sink its channel below the flood-plain which the earlier and perhaps smaller stream had developed.

(4) Any stream which has reached the flood-plain stage is likely to meander. After the flood-plain has become wide, the width of the belt within which the stream meanders is less than the width of its plain. In the Lower Mississippi, for example, the meander belt is often no more than a third to a tenth of the width of the flood-plain. The meanders migrate down the valley. In so doing they depress the meander belt, the tendency being to reduce it to the level of the channel, and, therefore, below the level of the flood-plain. As the meander belt widens, the depression which it develops becomes more and more capacious. Presently it may attain such dimensions as to hold the water of ordinary floods. At this stage, or even before, such parts of the earlier flood-plain as remain are terraces.

Terraces developed by the normal activities of a stream are always low, and it is improbable that they would ordinarily be conspicuous.

In conclusion, it may be stated that many river terraces, mostly very low, are normal features of valley development, coming into existence at definite stages in a valley's history. They are generally composed, in large part, of river alluvium. Others result from more or less accidental causes, working singly or in conjunction, and to this class belong all of the more conspicuous terraces developed from flood-plains.

Discontinuity of terraces. Where a stream's deepened channel is in the middle of its flood-plain, there is, temporarily, a terrace on either side; but wherever the deepened channel is at one margin of its flood-plain, a terrace remains on the other side only. Even where continuous at the outset, terraces soon become discontinuous, for all processes of subaërial erosion conspire to destroy them. A stream is likely to meander on its second and later flood-plains, as on its first and highest one. Wherever the meanders on its second flood-plain undercut the first terrace, the terrace at that

point may be destroyed, and since the meanders are continually migrating, terraces are continually disappearing. The same would be true of the second terrace, if a second is developed. Again, tributary streams cut through the terraces of their mains. New gullies develop on the faces of the terraces, and their heads work back across them, dissecting them still further. At the same time, sheet erosion and other phases of slope wash tend to drive the scarps of the terraces back toward the bluff beyond. By the time a second series of terraces is well developed, no more than meagre remnants of the first may remain.

From the foregoing considerations it is clear that the present extent of river terraces once developed, is dependent in part on the length of time which has elapsed since the river sank its channel below them. Other things being equal, the greater their age the more meagre their remnants.

Alluvial terraces, like rock shelves, are popularly thought to mark "old levels of the river." In one sense this is true, but not in the sense in which the expression is commonly used. Every level, from the crest of the bounding bluffs to the bottom of a valley, is a level at which water ran for a longer or shorter time; but the terrace does not mean that the river was once so much larger than now as to fill the valley from its present channel to the level of the terraces.

Laboratory work. The study of topographic and geologic maps, and of photographs, slides, etc., illustrating river work should be taken up in connection with this chapter. Numerous sheets of the topographic maps and several of the folios published by the United States Geological Survey afford available illustrations of river work. Plates XXIII-LXXXIX of Professional Paper 60 of the United States Geological Survey also afford good illustrations. This work should not be left until the chapter has been completed, but may well be sub-divided. Illustrations of *stream erosion* under varying conditions and at various stages of development; the *topographic effect of unequal hardness*; *structural adjustment* and *piracy*; *effects of change of level*; *cycles of erosion*; *alluviation*, etc., may best be taken up in connection with the discussion of these several topics.

CHAPTER V

GROUND- (UNDERGROUND) WATER

Many familiar facts demonstrate the presence of abundant water beneath the surface. The thousands of wells in lands peopled by civilized man, and the many springs which issue from the slopes of mountains and valleys are sufficient proof both of the wide distribution of ground-water and of its great abundance.

Certain well-known facts make it clear that ground-water is intimately connected with rainfall. The level of the water in wells commonly sinks during droughts, and rises after rains; and the sinking is greater when the drought is long, and the rise is more notable when the rainfall is heavy. Many springs flow with reduced volume in times of drought, and others cease to flow altogether. Furthermore, rain-water is seen to sink beneath the surface, wherever the soil is porous. Sinking through the soil to the solid rock, it finds cracks and pores, and through them it descends to greater depths. Nowhere are the rocks beneath the mantle rock so compact and so free from cracks, when any considerable area is considered, as to prevent the percolation of water through them. The conditions which influence the amount of water which sinks beneath the surface have been mentioned (p, 110).

Supply of ground-water not altogether dependent on local rainfall. The amount of ground-water in a given region does not always depend entirely on the local rainfall. Ground-water is in constant movement, and entering the soil or rock at one point it may, after a subterranean journey, reach a point far from that where it entered. Thus beneath the Great Plains of the West there is much subterranean water which fell on the eastern slopes of the Rocky Mountains. It has flowed beneath the surface to the plains where some of it is now drawn out for purposes of irrigation in

regions where rainfall is deficient. The accompanying diagram (Fig. 164) illustrates the flow here described.

The ground-water surface. Water table. The water table has already been defined (p. 117) as the upper surface of the ground-water. In a flat region of uniform structure, the ground-water surface is essentially level, though it rises and sinks with the rainfall.



Fig. 164.— Diagram showing how rainwater, falling in one place, may flow underground to another and there be brought to the surface. The layer *a* is porous, and water entering it in the mountains follows it to the plain.

Where the topography of a region is not flat, the ground-water surface is not level. As a rule it is higher (though farther below the surface) under an elevation than under surrounding lowlands, as illustrated by Fig. 165. The reason is understood readily. If a hill of sand is exposed to rainfall, most of the water falling on its porous surface sinks into it. If the precipitation continues long enough, as in a protracted rain, the hill of sand will be filled with

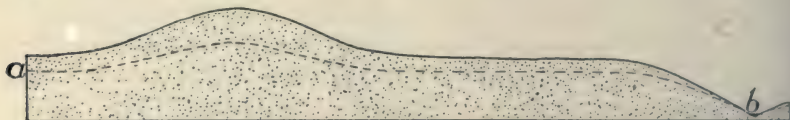


Fig. 165.— Diagram illustrating the position of the ground-water surface (the dotted line) in a region of undulating topography.

water, the water occupying the interstices between the grains. The water in the hill tends to spread, but since the movement involves friction, the spreading is slow. With the spreading, the surface of the water in the sand sinks, and sinks fastest at the center where it is highest (Fig. 165). If no more water were added, the surface of the water in the hill would, in time, sink nearly to the level of the water in the surrounding land; but at every stage preceding the last, the surface of the water would be higher beneath

the summit of the hill than elsewhere, though farther from the surface. In regions of even moderate precipitation the water-surface beneath the hills rarely sinks to the level of that in the lowlands about them, before it is raised by further rains.

The water-surface beneath the lowlands also sinks. Some of it finds its way into valleys, some of it sinks to greater depths, and some of it evaporates; but since the water-surface beneath the elevations sinks more rapidly than that beneath the lowlands, the two approach a common level. Their difference will be least at the end of a drought, and greatest just after heavy rains.

Depth to which ground-water sinks. The depth to which ground-water penetrates has not been determined by actual observation. The deepest borings or excavations of any sort are little more than a mile deep, and at this depth there is nothing to indicate that the limit of water is being approached. There is a popular belief that water sinks until it reaches a temperature sufficient to convert it into steam; but except for special localities where hot lava lies near the surface, this belief does not appear to be well founded.

Assuming the temperature of water sinking beneath the surface to be 50° F., its temperature must be raised 162° to bring it to the temperature at which it would boil at sea-level. With this initial temperature, the following table shows the depths at which water would reach a temperature of 212° F. under various assumptions as to the rate of increase of temperature. It shows also the pressure in atmospheres which would exist at these several depths if the overlying rock were full of water.

Rate of Increase of Temperature Initial temperature 50° F.	Depth at which Temperature of 212° would be reached	Equivalent Pressure in Atmospheres
1° for 50 feet	8,100 feet	238 (approximately)
1° for 75 "	12,150 "	357 "
1° for 100 "	16,200 "	478 "

The temperature at which water boils increases with the pressure. A pressure of about 200 atmospheres is the *critical pressure* for water; that is, the pressure which, if increased, will prevent boiling altogether. The depth at which a pressure of 200 atmospheres

would be reached, supposing the upper rock to be full of water, is about 6,800 feet. The temperature of the water at this depth, under various assumptions, is shown in the following table:

Initial Temperature	Rate of Increase of Temperature	Temperature at a depth of 6,800 feet
50°	1° for 50 feet	186° Fahr.
50°	1° for 75 "	141° "
50°	1° for 100 "	118° "

None of these temperatures is so high as the boiling-point of water *at sea-level*. It is therefore clear that at this depth, water has not even closely approached the boiling temperature *for this depth*, and since this is the depth of the critical pressure, it cannot boil at any greater depth, where the pressure would be greater. The descent of water is therefore not stopped, under normal conditions of crustal temperature, because it reaches its boiling-point. Locally, as in the vicinity of active or recently extinct volcanoes, the case may be different.

It is conceivable that water may descend until it reaches its *critical temperature*, that is, the temperature which, if increased, will cause the water to become water-gas in spite of pressure. The critical temperature is somewhere between 610° and 635°. The depth at which the critical temperature would be reached, under various assumptions, is shown in the following table:

Initial Temperature	Rate of Increase of Temperature	Depth of Critical Temperature
50°	1° for 50 feet	28,000 to 29,250 feet
50°	1° for 75 "	42,000 to 43,125 "
50°	1° for 100 "	56,000 to 57,500 "

There is good reason, in the increasing density beneath the surface, and on other grounds as well, for believing that the rate of increase of temperature decreases with depth, and therefore that the rate of 1° for 50 feet for the depths concerned is far too high. The greater depths of the table above are therefore believed to more nearly represent the truth than the lesser ones. If this is correct, the depth at which the critical temperature would be reached is probably not less than 50,000 feet.

If descending water reached its critical temperature by going down to these great depths, the extent to which the resulting *water-gas* might be absorbed into the interior of the earth is not known. *So far as limited by temperature*, therefore, it is not possible to assign a limit to the descent of water under average conditions of crustal temperature.

But there is reason to think that water does not go down to the depths necessary for the critical temperature. Rock, solid and unyielding as it seems, is yet mobile under sufficiently great pressure. Cracks and cavities are believed to affect it to depths which are slight in comparison with the radius of the earth. If openings were formed at sufficient depths below the surface they could not persist, for the adjacent rock, under the pressure which there exists, would "flow" in and close them. The flow is, in effect (though not in principle) much like the flow of a stiff liquid. The outer zone of the earth where cracks and cavities may exist has been called the *zone of fracture*,¹ and the thickness of the zone of fracture is not believed to exceed six miles, even for the most resistant rock.² This depth is probably much less than that at which the critical temperature of water would be reached, as indicated in the last table.

If water descends through openings in the rock to a depth of six miles, it will, under the assumptions specified in the first and second columns of the following table, have the temperature indicated in the third column:

Initial Temperature	Rate of Increase of Temperature	Temperature at Depth of Six Miles
50°	1° for 50 feet	683° Fahr.
50°	1° for 75 "	472° "
50°	1° for 100 "	367° "

In the first of these cases, the temperature of the water at the assumed lower limit of the zone of fracture, is above the critical temperature of water. If the assumptions involved in this case are correct, water might descend to the point where it would be converted into water-gas, and in this condition it might be

¹ Hoskins. 16th Ann. Rept., U. S. Geol. Surv., p. 853.

² Van Hise. Principles of North American Pre-Cambrian Geology, 16th Ann. Rept., U. S. Geol. Surv.

occluded by the hot rock. In the other cases, which involve the more probable assumptions, the critical temperature is not approached closely at a depth of six miles. If pores and cracks do not extend to greater depths, liquid water could not; and since the water at this depth has probably not reached its critical temperature, it must still be in the form of liquid. It would seem, therefore, that the descent of water under ordinary conditions, is limited by the *zone of fracture*, rather than by temperature.

Some recent experiments suggest that, at high temperatures and under great pressures, water may enter into combination with rock material, with contraction of volume.¹ If this is correct, water (in some form of combination) may perhaps go down below the zone of fracture.

Movement of ground-water.² Ground-water is in more or less continual movement. If all the water is pumped out of a well, it soon fills up again by inflow from the sides. Springs and flowing wells also demonstrate the movement of ground-water. Near the surface the movement is primarily downward if the rock through which it passes is equally permeable in all directions; but so soon as the descending water reaches the water-surface, its downward flow is checked, and its movement is partly lateral.

Ground-water moves chiefly by slow percolation, for most of it is not organized into definite streams. Small streams are seen in some caves, and subterranean streams issue as springs in some places; but most streams which issue as springs probably have definite channels for short distances only, before they appear at the surface. It is probable that ground-water frequently flows in considerable quantity along somewhat definite planes, without having open channels. This is the case especially along the surface of an impervious layer overlain by a porous one. The "reservoirs" from which artesian wells draw their supply are not usually streams or lakes, but porous beds of rock, containing abundant water. As the supply is drawn off at one point, it is renewed by

¹ Barus. Bull. 92, U. S. Geol. Surv.

² For a full discussion of this subject see King, 19th Ann. Rept., U. S. Geol. Surv., Pt. II, and Slichter, Water Supply and Irrigation Paper No. 67, U. S. Geol. Surv.

water entering elsewhere. Since the freedom of movement of ground-water is influenced greatly by the porosity of the rock, and since the rock is, on the average, most porous near the surface, the movement of ground-water is, on the whole, greatest near the surface and least at its limit of descent. It follows that while the upper part of the ground-water, especially that above ground-water level, moves somewhat freely, the lower part moves more slowly. It is probable, indeed, that movement in the lower part of the subterranean hydrosphere is extremely slow.

The amount of ground-water. The porosity of surface rocks varies widely, and the porosity of but few has been determined.¹ From such determinations as have been made, it is estimated that the average porosity of the outer part of the lithosphere is somewhere between five and ten percent. If the porosity diminishes regularly to a depth of six miles, where it becomes zero, the average porosity to this depth would be half the surface porosity.² An average porosity of two and one-half per cent would mean that the rock contains enough water to form a layer nearly 800 feet deep, if brought out to the surface.³ For the reason indicated in the second foot-note below, it may be that this figure is too large, even for the land. The porosity beneath the sea is probably less than that beneath the land, so that for the earth, this figure is perhaps too high, and is not to be regarded as a measurement. It is the water beneath the surface which justifies the term *hydrosphere*, as applied to the waters of the earth.

Fate of ground-water. Most of the water which sinks into the earth reaches the surface again after a longer or shorter journey. Some of it is evaporated from the surface directly; some of it is

¹ For tables see Buckley, *Building and Ornamental Stones*, Bull. IV, Wis. Surv.; Merrill, *Stones for Building and Decoration*; and various Survey Reports.

² It is probable that the porosity decreases in more than an arithmetic ratio, both because the deeper rocks are not so generally of porous kinds, as at the surface, and because of the pressure which tends to close openings.

³ Slichter (op. cit., p. 15) estimates that the ground-water is sufficient in amount to cover the earth's surface to a depth of 3,000 to 3,500 feet. Earlier estimates (Delesse, Bull. Soc. Geol., France, Second Series, Vol. XIX, 1861-62, p. 64) gave still higher figures. Fuller, in a recent estimate, places the amount much lower, about 100 feet. Water Supply and Irrigation Paper 160, U. S. Geol. Survey.

taken up by plants and is passed by them into the atmosphere; some of it issues in the form of springs; some of it seeps out; some of it is drawn out through wells; and much of the remainder finds its way underground to the sea or to lakes, issuing as springs beneath them. A small portion of the descending water enters into permanent combination with mineral matter. Many minerals are known to take up water, being changed thereby from an *anhydrous* to a *hydrous* condition. It does not necessarily follow, however, that the total supply of water is thereby decreasing. Minerals once hydrated may be dehydrated, the water being set free. Furthermore, considerable quantities of water in the form of vapor issue from volcanoes, and volcanic vents often continue to steam long after volcanic action proper has ceased. It is probable that some, and perhaps much of the water issuing from these vents has never been at the surface before. The amount of water reaching the surface of the earth for the first time from volcanoes, may, so far as now known, equal or even exceed the amount consumed in the hydration of minerals.

THE WORK OF GROUND-WATER

Ground-water is ever active. The results of its work are partly chemical and partly mechanical, the former being the more important.

The Chemical Work

The results of the chemical and chemico-physical action of water may be grouped in several more or less distinct categories.

1. The simplest effect is the solution of mineral matter. Pure water will dissolve certain minerals; but the carbon dioxide extracted from the atmosphere, and the products of organic decay extracted from the soil give ground-water a power to dissolve which is not possessed by pure water. The solvent work of ground-water is shown by the fact that all such water, whether it issues as springs or is drawn out through wells, contains mineral matter, while rain water is essentially free from it. The subtraction of soluble matter from rock tends to make it porous, and helps it to decay.

2. One mineral substance in solution may be exchanged for another extracted from the rock. Thus the lime carbonate of a

shell imbedded in rock may be removed, molecule by molecule, and some other substance, such as silica, left in its place. When the process is complete, the substance of the shell has been completely removed, though its form and structure are still preserved in the new material which has taken the place of the old. Buried logs are sometimes converted into stone by the substitution of mineral matter for the vegetable tissue. This is *petrification* (Fig. 167). Solution is a necessary antecedent of substitution.

3. The materials which are subtracted from the rock at one point may be added to other rock elsewhere. Thus a third type of change, *addition*, is effected. Rock may at one time and place be rendered porous by the subtraction of some of its substance, and the openings thus formed may subsequently become the receptacles of deposits from solution. This is exemplified in the stalactitic deposits of many caves. Not uncommonly cracks and fissures are filled with mineral matter deposited by the waters which pass through them. Thus arise *veins* (Fig. 20) which, for the most part, are cracks and crevices filled by mineral matter brought to them in solution, and precipitated on their walls. Most veins of metallic ores originated in this way.

4. A further series of changes is effected by ground-water when it, or the mineral matter it contains, enters into combination with the mineral matter through which it passes. One of the commonest processes of this sort, hydration, has already been referred to (p. 102); but in the development of many of the commoner hydrous minerals, changes other than hydration are involved. These changes result in *new mineral combinations*, the new minerals being developed out of the old, usually with some additions or subtractions. In the long course of time, changes of this sort may be so great as to change rock radically, both chemically and physically.

Quantitative importance of solution. In general, solution is probably most effective at a relatively slight distance below the surface. In the mantle rock, the materials are usually less soluble than below, for in many places they represent the residuum after the soluble parts of the formation from which they originated were dissolved out. Below this zone the rock contains more soluble

matter, and the water, charged with organic matter in its descent through the soil, is in condition to dissolve it. At greater depths the water has become saturated to some extent, and, so far forth, less active. Here, too, the movement is less free. The increased pressure at considerable depths, on the other hand, facilitates solution, which must be understood to take place under proper circumstances in any zone reached by the water.

Calculations have been made which illustrate in a measure the quantitative importance of the solution effected by ground-water, for the mineral matter dissolved in streams is largely from ground-water. In the case of several streams, among them the Thames and the Elbe, careful estimates of the amount of dissolved mineral matter have been made. The Thames drains an area only about one-tenth as large as the State of New York, but it is estimated to carry about 1,500 tons of mineral matter in solution to the sea daily.¹ From the uppermost 20,000 square miles of its drainage basin, the Elbe is estimated to carry yearly about 1,370,000 tons of mineral matter in solution.

These figures make it clear that ground-water is an effective agent in the lowering of land surfaces. It is estimated that something like one-third as much matter is carried to the sea in solution as in the form of sediment, and that by this process alone land areas would be lowered something like one foot in 13,000 years.²

The quantitative importance of the solution effected by ground-water is shown in another way. It is probable that most of the salt now in the sea has been taken to it in solution by waters flowing in from the land. The amount of salt is stupendous (p. 289). Furthermore, most of the limestone of the earth has been extracted from sea-water, whither the larger part of it was carried by streams. The aggregate amount of limestone is far greater than the amount of salt in the sea. Some other sorts of rock, such as gypsum, of less importance quantitatively, have had a similar history. The total amount of rock which must have been decomposed to yield such quantities of calcium carbonate, sodium chloride, etc., is far greater than all the rock now above sea-level.

¹ Geikie. Text-book of Geology, 3d ed., p. 378.

² Reade. Liverpool Geol. Soc., 1876 and 1884.

Deposition of mineral matter from solution. The deposition of material from solution is effected in several ways. (1) It is sometimes deposited by *evaporation*. This is well shown where water seeps out on arid lands. (2) *Reduction of temperature* often occasions deposition. In general, hot water is a better solvent of mineral matter than cold,¹ and if it issues with abundant mineral matter in solution, the precipitation of some of it is likely to take place. (3) *Plants* sometimes cause the precipitation of mineral matter from solution. About some hot springs, even where the temperature of the water is very high, small plants of low type (algæ) grow in profusion. In ways which are not perfectly understood, these algæ extract the mineral matter from the hot water. They are now thought to be a chief factor in the deposits about the hot springs of the Yellowstone Park.² The influence of organisms on precipitation from solution is not confined to the waters of hot springs. (4) A fourth factor involved in the deposition of mineral matter from solution is *relief of pressure*. Pressure increases the solvent power of water. It also increases the amount of gas which may be dissolved, and the gas affects the solvent power of the water. As water charged with gas comes to the surface, the pressure is relieved and some of the gas escapes. Such mineral matter as was held in solution by the help of the gas which escapes, is then precipitated. (5) Precipitation is also sometimes effected by the mingling of waters containing different mineral substances in solution. Such mingling of solutions is most common along lines of ready subterranean flow, and while each portion of the water entering a crevice or porous bed might have been able to keep its own mineral matter in solution, their mingling may involve chemical changes, resulting in the formation of insoluble compounds, and therefore in deposition. This principle has probably been involved in the filling of many fissures and crevices, converting them into veins. (6) The disturbance of water, as by waves, some-

¹ This is not true in the case of minerals, such as lime carbonate, dissolved under the influence of gases in solution in the water.

² Weed. The Formation of Hot Springs Deposits; Excursion to the Rocky Mountains, and Ninth Ann. Rept. U. S. Geol. Surv., pp. 613-76; and B. M. Davis, Science, Vol. VI, pp. 145-57, 1897.

times causes its gases to escape, and so causes the deposition of mineral matter held in solution.

The deposition of material held in solution is most notable at two zones, one below that of most active solution, and the other at the surface, where evaporation is active. Under proper conditions, however, deposition may take place at any level reached by water.

Mechanical Work

The mechanical work of ground-water is relatively unimportant. Where it flows in definite streams, the channels through which it flows are likely to be increased by mechanical erosion as well as by solution. Either beneath the surface, or after the streams issue, the mechanical sediment carried will be deposited.

RESULTS OF THE WORK OF GROUND-WATER

Weathering. Where the solvent work of ground-water is slight and equally distributed, the result is to make the rock porous. If, for example, some of the cement of sandstone is dissolved, the texture of the rock becomes more open; but if all the cement is removed, the rock is changed from sandstone to sand. If a complex crystalline rock contains among its many minerals some one which is more soluble than the others, that one may be dissolved. This has the effect of breaking up the rock, since each mineral acts as a binder for the rest. It might happen that no one of the minerals is dissolved completely, but that some one of them is decomposed by water, and certain of its constituents removed. Such change would be likely to cause the mineral so affected to crumble, and with its crumbling, if it is an important constituent of the rock, the integrity of the rock is destroyed. The increase in volume attendant on hydration, etc., sometimes leads to the disruption of rock. These are phases of weathering.

Caverns.¹ Where local solution is very great, results of another sort may be effected. In formations like limestone, which are relatively soluble, considerable quantities of material are frequently

¹ For a racy and interesting account of caverns see Shaler's *Aspects of the Earth*.

dissolved from a given place. Instead of making the rock porous, in the usual sense of the term, large caverns may be developed

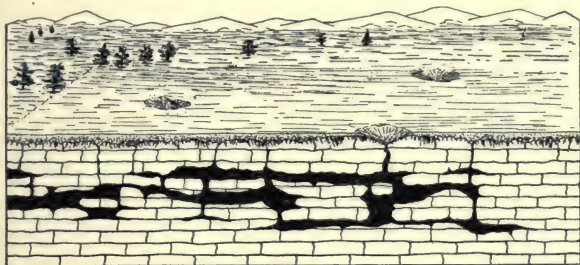


Fig. 166.— Diagram to illustrate the form and relations of caverns developed by solution. The black spaces represent caverns. Limestone sinks are represented at the surface where the roofs of caves have fallen in.

(Fig. 166). In their production, solution may be abetted by the mechanical action of the water passing through the openings which solution has developed.



Fig 167.— Sections of petrified logs, near Holbrook, Ariz. Beds probably Jurassic.

One of the best known regions of caves is in the basin of the Ohio in Kentucky and southern Indiana, where the number of caves is large, and the size of some of them, such as Mammoth and Wyandotte, very great. A ground-plan of Wyandotte (Ind.) Cave is shown in Fig. 168. The aggregate length of its passageways is a number of miles.

Deposition often takes place in caves after they are formed (Fig. 169), or it may even go on at the same time that the cave is being excavated. Stalactites and stalagmites are common forms of cave deposits. A stalactite may start from a drop of water leaking through the roof of the cave. Evaporation, or the escape of



Fig. 168.— Ground-plan of Wyandotte Cave. The unshaded areas represent the passageways. (21st Ann. Rept., Ind. Geol. Surv.)

some of the carbonic gas in solution, results in the deposition of some of the lime carbonate about the margin of the drop, in the form of a ring. Successive drops make successive deposits on the lower edge of the ring, which grows downward into a hollow tube through which descending water passes, making its chief deposits at the end. Deposition in the tube may ultimately close it, while deposition on the outside, due to the water trickling down in that position, may greatly enlarge it.

Limestone sinks. Underground caves sometimes give rise to topographic features of local importance. When the roof of a cavern becomes thin and weak, it may collapse, giving rise to a sink or depression in the surface over the site of the original cave. This is so common that regions of limestone caves are often affected by numerous sinks formed in this way. They are conspicuous in the cave region of Kentucky, and are well known in many other limestone districts, and are known as *limestone sinks* (Fig. 170 and Fig. 166, and Pl. XV).



Limestone sinks due to solution by ground-water. The depression contours are hachured. Scale, about 2 miles per inch. (Pikeville, Tenn., Sheet, U. S. Geol. Surv.)

Creep, slumps, and landslides. When the soil and subsoil on a slope become charged with water, they tend to move downward. When the movement is too slow to be sensible it is called *creep*; when rapid enough to be sensible, the material is said to *slump* or *slide*. This may happen when the slope on which water-charged mantle-rock lies is steep (Fig. 171). Some landslides have done great damage. Where a stream's banks are high, and of unin-



Fig. 169.—Stalactites and stalagmites in Marengo Cave, southern Indiana. (Hains.)

durated material, such as clay, considerable masses sometimes slump from the bank or bluff into the river, or settle away slowly from their former positions. This is a common phenomenon along streams which have cut valleys in drift, and along shores of drift on which waves are encroaching. The same phenomenon is common on a larger scale on the slopes of steep mountains.¹

In creep and in landslides gravity is the force involved, and the ground-water only a condition which makes gravity effective.

¹ Russell has emphasized this point in 20th Ann. U. S. Geol. Surv., Pt. 44, pp. 193-202, and Cross, 21st Ann. U. S. Geol. Surv., Pt. II, pp. 129-150.

Summary

All in all, *ground-water* is to be looked upon as a most important geological agent. When it is remembered that a very large part of all the water which falls on the surface of the earth, either in the form of rain or snow, sinks beneath the surface; that much of it sinks to a great depth; that much of it has a long underground course before it reappears at the surface; that it is everywhere and always active, either in *subtracting* from the rock through which it passes, in *adding* to it, in effecting the *substitution* of one

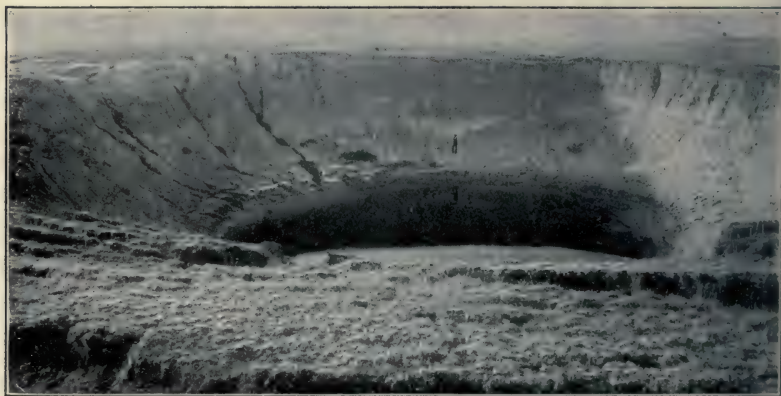


Fig. 170.— A sinkhole of recent development near Meade, Kan. (Johnson, U. S. Geol. Surv.)

mineral substance for another, or in bringing about *new chemical combinations*; and when it is remembered that these processes have been going on for untold millions of years, it will be seen that the total result accomplished must be great. The rock formations of the earth to the depths to which ground-water penetrates are to be looked upon as a sort of chemical laboratory through which waters are circulating in all directions, charged with all sorts of mineral substances. Some of the substances in solution are deposited beneath the surface, and some are brought to the surface where the waters issue. Much of the material brought to the surface in solution is carried to the sea and utilized by marine organisms in the making of shells. Without the mineral matter

brought to the sea by springs and rivers, many shell-bearing animals of great importance, geologically, would perish. Biologically, therefore, as well as geologically, ground-water is of great importance.

SPRINGS

Springs. The term *spring* is applied to any water which issues from beneath the surface with sufficient volume to cause a distinct current. If the water issues so slowly as to merely keep the surface



Fig. 171.—South face of Landslip Mountain, Colo. The protruding mass on the right has slumped down. (U. S. Geol. Surv.)

moist, it is not called a spring, but *seepage*. The spring from which water issues with a strong current, especially if it is upward, is comparable to a flowing well, while the spring from which water issues with little force, and without upward movement, is comparable to the flow of water into a common well.

Springs often issue from the sides of valleys (Fig. 172), the bottoms of which are below ground-water level. They are especially likely to issue at the surface of relatively impervious layers,

and where the valley slopes cut joints, porous beds, or other structures which allow free flow of ground-water.

Springs are classified in various ways, and the several classifications suggest characteristics worthy of note. They are sometimes classed as *deep* and *shallow*, but the idea involved in this grouping would be better expressed by *strong* and *feeble*. Springs are also classified as *cold* and *thermal*, the latter term meaning simply that the temperature is such as to make the springs seem warm or hot. The temperature of thermal springs ranges up to the boiling-point of water. Between deep springs and shallow ones, and between cold springs and warm ones, respectively, there is no sharp line of demarkation. Again, some springs are continuous

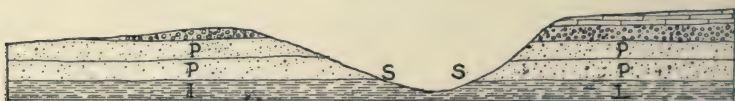


Fig. 172.— Diagram showing conditions favorable for a spring in the side of a valley. P and P represent porous beds of rock, and I, an impervious bed. Rainwater sinks to I, and moving along its surface, may come out as a spring at S.

in their flow, while others are *intermittent*. Most intermittent springs flow after periods of precipitation, but dry up during droughts. Springs are also classified as *mineral* and *common*. Mineral springs, in the popular sense of the term, are of two types: (1) Those which contain an unusual amount of mineral matter, and (2) those which contain some unusual mineral. All springs which are not mineral are *common*. This classification is not very significant, for all springs contain more or less mineral matter, and many springs which are common contain more mineral matter than some springs that are mineral. Mineral springs are themselves classified according to the kind and amount of mineral matter they contain. Thus *saline* springs contain salt; *sulphur* springs contain compounds (especially gaseous) of sulphur; *chalybeate* springs contain iron compounds, especially the sulphate; *calcareous* springs contain abundant lime carbonate, etc. These various mineral substances have been extracted from the rock. The salt

of saline springs is usually extracted from beds of salt beneath the surface. Lime carbonate, one of the commonest substances in solution in ground-water, is dissolved from limestone, or derived by chemical change from rocks containing some calcium compound. Thus lime feldspars, by carbonation, give rise to lime carbonate. Chalybeate waters often arise from the oxidation of iron sulphide (a mineral which is common in many sedimentary rocks) and the solution of the resulting sulphate. *Medicinal* springs are those which contain some substance or substances which have, or are supposed to have, curative properties.

Mineral matter in solution. The number and variety of mineral substances in spring water is very great, and the amount of solid matter in solution varies widely. Some of the hot springs of the Yellowstone Park contain nearly three grams (2.8733) of mineral matter per kilogram.¹ The springs of Leuk (Switzerland) bring to the surface annually more than 2,000 tons of calcium sulphate (gypsum) in solution, and in the same time the springs of Bath (England) bring up an amount of mineral matter in solution sufficient to make a column 9 feet in diameter, and 140 feet high.²

Geysers. Geysers are intermittently eruptive hot springs. They occur only in volcanic regions (past or present), and in but few of them, being known only in the Yellowstone National Park, Iceland, and New Zealand. There are said to be more than sixty active geysers in the Yellowstone Park.

The cause of the eruption is steam. The surface-water sinks down until, at some unknown depth, it comes into contact with rock sufficiently hot to boil it. The source of the heat is not open to inspection, but it is believed to be the uncooled part of extruded or intruded lava. From what was said earlier in this chapter it is clear that geysers do not have their origin in water which sinks down to the zone of great heat, where the downward increment of heat is normal.

The water of a geyser issues through a tube of unknown length. Whether the tube is open down to the source of the heat is not determinable, but water from such a source finds its way to the tube.

¹ Gooch and Whitfield. Bull. 47, U. S. Geol. Surv.

² Geikie. Text-book of Geology, 3d ed., p. 367.

Water may enter the tube from all sides and at various levels. The heating may precede or follow its entrance into the tube, or both. So far as the water is heated after it enters the tube, the point of most rapid heating may be at the bottom of the tube, or at some point above. If the temperature of the source of heat were high enough to convert the descending water into steam as fast



Fig. 173.— Giant Geyser, Yellowstone National Park. (Wineman.)

as it enters the tube, the steam would escape continuously, and there would be no geyser; but if the rock is only hot enough to bring the water to the boiling-point after some lapse of time, and after some water has accumulated, an eruption is possible.

The exact sequence of events which leads up to an eruption is not known, but a definite conception of the principles involved may perhaps be secured by a definite case. Suppose a geyser-tube full of water and heated at its lower end. As the water is heated below, convection tends to distribute the heat throughout the column

of water above. If convection were free and the tube short, the result would be a boiling spring; but if the tube is long, and especially if convection is impeded, the water at some level below the surface may be brought to the boiling-point earlier than at the top. Under these circumstances if even a little water in the lower part of the tube is converted into steam, the steam will raise the column of water above, and it will overflow. The overflow relieves the pressure on all parts of the column of water below the surface. If before the overflow there was any considerable volume of water



Fig. 174.—The cone of Lone Star Geyser, Yellowstone National Park.
(U. S. Geol. Surv.)

essentially ready to boil, the relief of pressure following the overflow might allow it to be converted into steam suddenly, and the sudden conversion of any considerable quantity of water into steam would cause the eruption of all the water above it (Fig. 173). The height to which the water would be thrown depends upon the amount of steam, the size and straightness of the tube, etc.

It is clear that everything which impedes convection in the geyser tube will hasten the period of eruption, since impeded circulation will have the effect of holding the hot water down, and so of bringing the water at some level below the top more quickly to the boiling-point. It follows that anything which chokes the

tube, or which increases the viscosity of the water, hastens an eruption.¹

Geysers often build up crater-like basins or cones (Figs. 174 to 176) about themselves, the cone being of material deposited from solution. In the Yellowstone Park, the precipitation of the matter in solution (chiefly silica) is partly due to cooling, but largely to the algæ which abound even in the boiling water, and the



Fig. 175.— Cone (or crater) of Grotto Geyser, Yellowstone Park. (Detroit Photo. Co.)

brilliant colors of some of the deposits about the springs are attributable to these plants. When the water from any geyser or hot spring ceases to flow, the plants die and the colors disappear.

The heating of geyser water must cool the lava or other source of heat below. As this takes place, the time between eruptions becomes longer and longer. In the course of time, therefore, the geyser must cease to be eruptive, and when this change is brought about the geyser becomes a hot spring. Within historic time

¹ Weed. Ninth Ann. Rept. U. S. Geol. Surv., pp. 613-76, and Am. Jour. Sci., Vol. XXXVII, 1889, pp. 351-59.

several geysers have ceased to erupt and new ones have been developed. In the Yellowstone Park, where there are said to be something like 3,000 vents of all sorts, hot springs which are not eruptive



Fig. 176.— Deposit from a hot spring in Yellowstone Lake. (Fairbanks.)



Fig. 177.— Hot springs deposits, Mammoth Hot Springs, Yellowstone Park.

greatly outnumber the geysers. From many of the vents but little steam issues, and from some, little else.

A few geysers have somewhat definite periods of eruption. Of such "Old Faithful" is the type; but even this geyser, which formerly erupted at regular intervals of about an hour, is losing the reputation on which its name is based. Not only is its period of eruption lengthening, but it is becoming irregular, and the irregularity appears to be increasing. In the short time during which this geyser has been under observation its period has changed

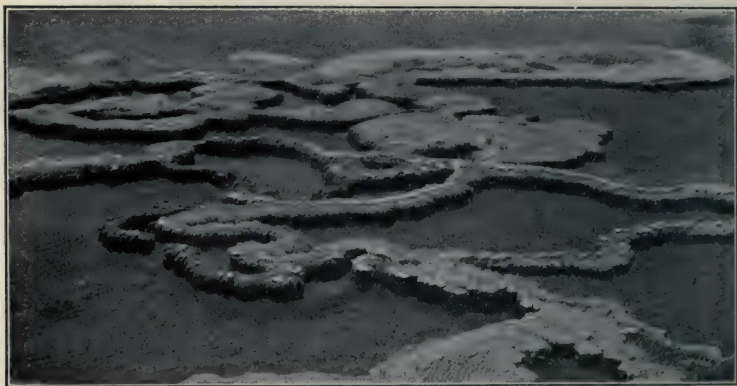


Fig. 178.—Deposits in the hot waters about Biscuit Geyser, Yellowstone Park. (Fairbanks.)

from a regular one of 60 minutes, or a little less, to an irregular one of 60 to 90 minutes. In the case of some geysers, years elapse between eruptions, and in some the date of the last eruption is so remote that it is uncertain whether the vent should be looked upon as a geyser or merely a hot spring.

In the Yellowstone Park the geysers are mainly in the bottoms of valleys (Fig. 179), but the deposits characteristic of geysers are found in not a few places well above the present bottoms. These deposits record the fact that in earlier times the geysers were at higher levels than now. It is probable that they have been, at all stages in their history, near the bottoms of the valleys, and that as the valleys have deepened, the ground-water has found lower

and lower points of issue. In this respect the geysers probably have had the same history as other springs.

Unless new intrusions of lava occur, or unless heat is otherwise renewed at the proper points, it is probable that all existing geysers will become extinct within a time which is, geologically, short. New geyser regions may, however, develop as old ones disappear.

Artesian Wells

The terms *artesian* wells and *flowing* wells were synonymous originally; but any notably deep well is now called *artesian*. The



Fig. 179.— Hot springs and geysers. Norris Geyser Basin, Yellowstone Park.

artesian well which does not flow does not differ from common wells in principle, while the flowing well is really a gushing spring, the opening of which was made by man.

Flowing wells¹ depend upon certain relations of rock structure, water supply, and elevation. Generally speaking, a flowing well is possible in any place underlain by any considerable bed of porous

¹ Chamberlin. Geol. of Wis., Vol. I, pp. 689-97, and Fifth Ann. Rept., U. S. Geol. Surv., pp. 131-73. The former a brief, and the latter an elaborate, exposition of the principles involved. The same principles in various forms of statement have appeared in later publications of the U. S. Geol. Surv.

rock, if this rock outcrops at a sufficiently higher level in a region of adequate rainfall, and is covered by a layer or bed of impervious or relatively impervious rock. This statement involves four conditions, all of which are illustrated by Fig. 180, where *a* is the bed of porous rock. It is not necessary that the beds of rock form a structural basin, nor is it usually necessary to take account of the character of the rock beneath the porous bed which contains the water.

The bed of porous rock is the "reservoir" of the flowing well. Formations of sand or sandstone, and of gravel or conglomerate,

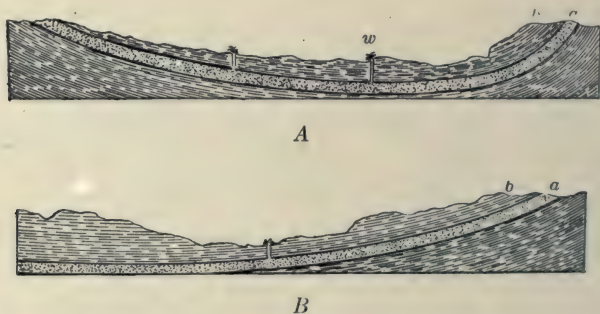


Fig. 180.—Diagrams illustrating conditions favorable for artesian wells. In A, the porous bed *a* is in the form of a basin; in B, it merely dips.

most commonly serve as the reservoirs. In order that they may contain abundant water they must have some thickness, and their outcropping edges must be so situated that the water may enter freely and be replenished, chiefly by rain, as the water flows out at the well.

A relatively impervious layer of rock above the reservoir (*b*, Fig. 180) is most important; otherwise the water in the reservoir will leak out, and there will be little or no "head" at the well site. Thus if the rock overlying stratum *a* (Fig. 180) were badly broken, the fractures extending up to the surface, the conditions would be unfavorable for flowing wells, for though wells in the positions of those in Fig. 180 might get abundant water, they would not be likely to flow. If the stratum next below the reservoir is not im-

pervious, some lower one probably is. No layer of rock is more impervious than one which is full of water, and the substructure of any bed which might serve as a reservoir is usually full of water, even when the rock, if free from water, would be porous.

If the outcrop of the reservoir is notably above the site of the well, and if it is kept full by frequent rains, the "head" will be

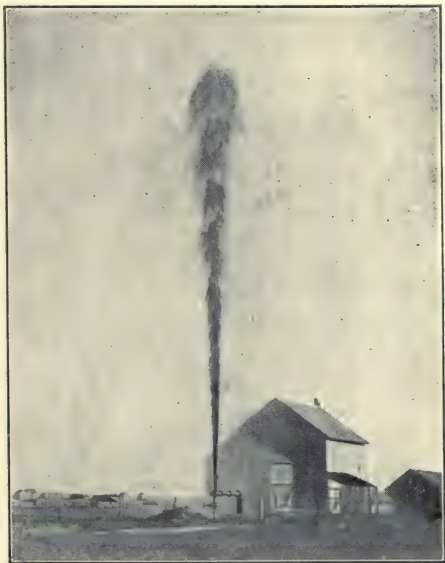


Fig. 181.— Artesian well at Woonsocket, S. D. (U. S. Geol. Surv.)

strong, though the water at the well will not rise to the level of the outcrop of the reservoir. Experience has shown that an allowance of about one foot per mile of subterranean flow should be made. Thus if the site of the well is 100 miles from the outcrop of the water-bearing stratum, and 200 feet below it, the water will rise something like 100 feet above the surface at the well. This rule is, however, not applicable everywhere. The failure of the water to rise to the level of its head is due chiefly to the friction of flow through the rock. The more porous the rock the less the friction. The height of the flow is also influenced by the number of wells

drawing on the same reservoir, on the degree of imperviousness of the confining bed above, etc. Flowing wells, often relatively shallow, are frequently obtained from unconsolidated drift.

Map work. Illustrations of the topographic effects of ground-water may be found on a few topographic maps. Plates XC to XCIV of Professional Paper 60, U. S. Geological Survey, are examples. Various reports on mining regions, showing structure sections, afford illustrations of the economic significance of one phase of work done by ground-water.

CHAPTER VI

THE WORK OF SNOW AND ICE

We have seen that the atmosphere, the ground-water, and the waters on the surface of the land bring about important changes in its configuration. Ice in its various forms is still another agent of change.

Ice beneath the surface. The wedge-work of ice in the crevices of rock has already been mentioned (p. 103). When the great areas where water freezes during some part of the year are considered, it is clear that the aggregate effect of the freezing of water in the pores and crevices of rock must be great in long periods of time. The water which freezes in the soil also has some effect on the surface. This is shown by the disturbance of the walls of buildings if their foundations do not go below the depth of freezing, and by the working up of stones and boulders through the soil of the fields, as freezing and thawing succeed each other. The frozen water in the soil makes it solid, and temporarily retards or prevents surface erosion.

Snow is more wide-spread than any other form of ice, but the ice of lakes and rivers is so wide-spread as to be well known. Ice on high mountains and in high latitudes is less familiar.

Ice on lakes and ponds. Since fresh water is densest at 39° Fahr., ice does not commonly form on the surface of a lake until the temperature from top to bottom is reduced to this point. Cooled below 39° , the surface water fails to sink, and reduced to 32° , it freezes. If the lake is small and shallow, it is likely to freeze over completely in any region where the temperature is notably below 32° for any considerable period of time. It is under these circumstances that the lake ice becomes most effective.

Let us suppose a lake in temperate latitudes, where the range of winter temperature is considerable, to be frozen over when the

temperature is 20° Fahr. If now the temperature is lowered to -10° , and such a change of temperature is not uncommon in the northern part of the United States, the ice contracts notably. In contracting, it either pulls away from the shores, or cracks. If the former, the water from which the ice is withdrawn quickly freezes; if the latter, water rises in the cracks and freezes there. In either cases, the ice-cover of the lake is again complete. If the temperature now rises to 20° the ice expands, and the solid cover



Fig. 182.—Shore of Wall Lake, Iowa. (Photo. by Calvin.)

becomes too large for the lake, and must either crowd up on the shores or arch up (wrinkle) elsewhere.

If the water near the shore is very shallow, the ice freezes to the sand, gravel, and bowlders at the bottom. If the land at the shore is very low, the ice in expanding may shove up over it, carrying the debris frozen in its bottom. It may even push up loose gravel and sand in front of its edge if they are present on the shore. Where bowlders are frozen to the bottom of the ice, the shore-ward thrust in expanding has the effect of shifting them in the same direction, and even of lifting them a little above the normal water-



Fig. 183.—Shove of shore ice where the shore is marshy. The ice of the frozen marsh is pushed up into ridges. (Buckley, Wis. Geol. Surv.)



Fig. 184.—The shove of ice on the shore of Lake Mendota, Wis. (Photo. by Buckley.)

level. This constant process of concentrating bowlders at the shore-line gives rise to the "walled" lakes (Fig. 182), which are not uncommon in the northern part of the United States. The "wall" does not commonly extend entirely around a lake. In making the walls, the ice driven up by the waves, especially in the spring when the ice is breaking up, co-operates.

If a lake is bordered by a low marsh, the ice and frozen earth of the latter are really continuous with the ice of the lake, and the push of the latter sometimes arches up the former into distinct anticlines, the frozen part only being involved in the deformation (Fig. 183). A succession of colder and less cold periods may give rise to a succession of such anticlines.¹ If the shore is steep, the crowding of the ice against a low cliff of yielding material, such as clay, disturbs all above the shore-line (Fig. 184). Where the cliff is sufficiently resistant, it withstands the push of the ice, and the ice itself is warped and broken.

Ice on rivers. Rivers also freeze over in cold climates, and when the ice breaks up in the spring, the stones and bowlders to which it was frozen in the banks are sometimes floated miles down the river. At Montreal stone buildings 30 to 50 feet square, projecting so as to have river ice form about them, have been moved by the ice of the St. Lawrence.

When the river ice breaks up, masses of it are carried downstream, and may accumulate in vast fields or "jams" behind obstructions in the river. Where a jam forms above a bridge, the bridge may be swept away. The jams also occasion disastrous floods above their sites, and when they break, the waters accumulated above may sweep down the valleys with destructive violence.

Northward-flowing rivers in the northern continents are especially subject to such floods. The snows of their upper basins often melt while the lower parts of the streams are still frozen over. The free discharge of the upper waters is thus prevented for a time, and freshets follow later.

Ice on the sea. In high latitudes, ice is formed along the sea-shore. Unlike fresh water, sea-water condenses until it freezes,

¹ Buckley, Wis. Acad. of Sci., Vol. XIII, Pt. I, 1900. A study of ice ramparts formed about the shores of Lake Mendota, Wis., in 1898-99.

at a temperature of 26° to 28° Fahr., the variation being due to the degree of salinity of the water.

In polar regions the sea ice attains a depth of several feet, at least as much as eight or ten. Floating ice of much greater thickness is sometimes seen, but it is doubtful if these great thicknesses represent the ice formed by the freezing of undisturbed sea-water. At any rate, the ice formed in winter is often broken up in summer into floating pieces called *floe-ice* (Fig. 185). Floe-ice is sometimes



Fig. 185.— Floe-ice on the shore of Greenland.

crowded together in *ice-packs*, the separate pieces being so jammed together that some of them are ended up and stand high above the water. If the ice-pack of one summer is still far enough north at the end of the warm season, it is frozen together, and its aggregate thickness, made up as it is of blocks of ice some of which are on edge, is far beyond that of normal sea ice.

Snow-fields. Over the larger part of the land, the snow of winter does not endure through the summer, and when it melts it follows the same course as rain; but in cold regions where the fall of snow is heavy, some of it remains unmelted from year to year, and constitutes perennial snow-fields.

High mountains and the lands of high latitudes are the common habitats of snow-fields. In North America there are numerous

small snow-fields in the western mountains, from Mexico on the south to Alaska on the north, their number and size increasing in the latter direction. In the United States there are few snow-fields south of the parallel of $36^{\circ} 30'$, and most of the many hundreds north of that latitude (excluding Alaska) are small. Farther north, the snow-fields of the western mountains attain greater size. Snow-fields comparable to those of the northwestern part of the United States and British Columbia occur in the higher mountains of Europe and Asia, while in South America there are snow-fields



Fig. 186.— Map showing the ice-cap of Greenland. Only the borders (shaded parts) of the island are free from ice.

of small size even in equatorial latitudes, and in the Chilean Andes there are some of considerable size. Small snow-fields occur on the highest peaks of tropical Africa, and in the mountains of New Zealand. For reasons which will appear later, much of every large snow-field is really ice.

Besides these fields of snow in mountain regions, there are fields of much greater extent in polar regions. The greater part of Greenland is covered with a single field of ice and snow, the size of which is estimated at 300,000 to 400,000 square miles (Fig. 186),—an area 400 to 600 times as large as the snow-and-ice-covered area of Switzerland. Numerous islands to the west of North Greenland are also partly covered with snow. In Antarctica there is a still larger field, the largest of the earth. Its area is not even approximately known, but such data as are at hand indicate that it may have an extent ten times as great as that of Greenland.

The only condition necessary for a snow-field is an excess of snow-fall over snow-waste. The lower edge of a snow-field, the

snow-line, is dependent chiefly on temperature and snow-fall. In general it does not depart much from the summer isotherm of 32° , though it may be above this isotherm where the snow-fall is light. That the snow-line is not a function of temperature only, is shown by its position in various places. Thus in the equatorial portion of the Andes, the snow-line has an altitude of about 16,000 feet on the east side of the mountains, where the precipitation is heavier, and of about 18,500 feet on the west side, where it is lighter. For the same reason the snow-line in the Himalayas is lower on the south side than on the north. Though temperature and snow-fall are the most important factors controlling the position of the snow-line, both humidity and the movements of the air are of some importance, since both affect the rate of evaporation of snow and ice.

The passage of snow into névé and ice. The snow does not lie on the surface long before it undergoes obvious change. The light flakes are transformed into granules, and the snow becomes "coarse-grained." The granular character, so pronounced in the last banks of snow in the spring, is even more distinct in perennial snow-fields. This granular snow is called *névé*. Where the thickness of the snow is great, the *névé* becomes more compact below, and finally grades into porous ice. Ice is found in some snow-fields at no great depth from the surface.

Structure of the ice. Ice formed beneath a snow-field is in some sense *stratified*. It is made up of successive falls of snow which tend to retain their individuality to some extent. Thus the snow of one season, or of one period of precipitation, may have been considerably changed before the succeeding fall of snow. Again, the surface of the snow-field at the end of the melting season is often covered with a visible amount of earthy matter, some of which was blown up on the surface during the melting season, and some of which was concentrated at the surface by the melting of the snow in which it was originally imbedded. The amount of earthy matter is often sufficient to define snows of successive years, and makes distinct the stratification which would otherwise remain obscure.

In addition to its stratification, the ice of the deeper portions

often acquires a stratiform structure which may perhaps best be called *foliation*, to distinguish it from the stratification which arises from deposition. The foliation appears to be akin to slaty cleavage or to schistosity, and to result largely from the shearing of one part over another in the course of the movements to which the ice is subjected, as will be illustrated presently.

Texture. The ice derived from the snow is formed of interlocking crystalline grains. The crystalline character is assumed by the snow-flakes when they form, and the subsequent changes which the snow undergoes seem only to modify the original crystals by building up some and destroying others. By the time the snow is converted into *névé*, the granules have become coarse, and wherever the ice derived from the *névé* has been examined, the granular crystalline texture is present. The individual crystals in the ice are usually larger than those of the *névé*, and more closely grown together. In compact ice the crystals are so intimately interlocked that they are not readily seen by the eye; but when the ice has been honeycombed by partial melting, the granules become partially separated and may be easily seen. While a given mass of snow in a great snow-and-ice-field cannot be followed uninterruptedly through its whole history, yet since the granular texture is pronounced in the *névé* stage where the granules show evidences of growth, and since the same texture is also pronounced in the last stages of the ice when it is undergoing dissolution, as well as at all observed intermediate stages, it is legitimate to assume that a granular crystalline condition persists throughout all stages of the history of the ice, and that it is a feature of progressive growth.

Inauguration of movement. When the snow and ice in a snow-field become very deep, motion is developed. The exact nature of the motion has not been demonstrated to the satisfaction of all who have studied the problem, though much is known about it. Brittle and resistant as ice seems, it may, under proper conditions, be made to exhibit some of the characteristics of a plastic substance. A piece of ice may be made to change its form, and may even be moulded into almost any desired shape if carefully subjected to sufficient pressure, steadily applied through long intervals of

time.¹ These changes may be brought about without visible fracture, and have been thought to point to a viscous condition of the ice. There is much reason, however, to question this interpretation. Whatever the real nature of the movement, the aggregate result of the movement in a field of ice is comparable, in a superficial way at least, to that which would be brought about if the ice were capable of moving like a viscous liquid, the motion taking place with extreme slowness. This slow motion of ice in an ice-field is glacier motion, and ice thus moving is *glacier ice*.

GLACIERS

Types. The different shapes of glaciers have given rise to different names. If the surface on which the ice-sheet develops is plane, the ice will move outward in all directions, and ice spreading in all directions from a center is an ice-cap. The glacier covering the larger part of Greenland (Fig. 186) is a good example. The glaciers on some of the flat-topped peninsular promontories of the same island are good examples of small ice-caps (Fig. 187). If ice-caps cover a large part of a continent, as some of those of the past have done, they are called *continental glaciers*.

Where ice-caps lie on plateaus whose borders are trenched by valleys, ice-tongues from the edge of the ice-cap may extend down the valleys, and constitute one type of *valley glacier*. A second and more familiar type of valley glacier occupies mountain

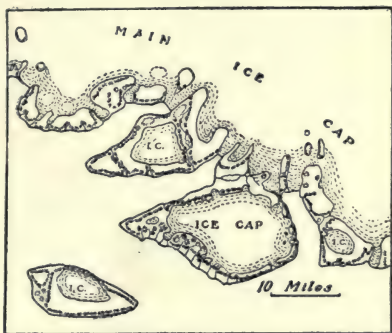


Fig. 187.— Ice-caps of small size. The figure also shows some valley glaciers extending out from the main ice-sheet and from the local ice-caps. A portion of the North Greenland coast, north of Inglefield Gulf. Lat. about 78°.

¹ For an account of experiments illustrating the mobility of ice see Aitkin, *Am. Jour. Sci.*, Vols. V, 1873, p. 305, and XXXIV, 1887, p. 149, and *Nature*, Vol. XXXIX, p. 203.

valleys, and is the offspring of mountain snow-fields. The former type, confined chiefly to high latitudes, are *polar* or *high-latitude* glaciers (Fig. 189); the latter are *alpine* glaciers (Figs. 190-192). The end and side slopes of high-latitude glaciers are, as a rule, much steeper than those of alpine glaciers.

When a valley glacier descends through its valley to the plain beyond, its end spreads. The deploying ends of adjacent glaciers

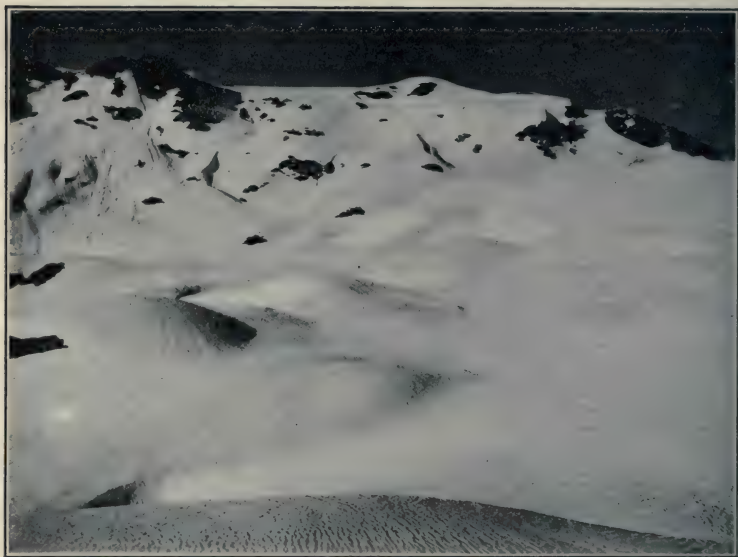


Fig. 188.— New snows of the Cascade Mountains, Washington.

sometimes merge, and the resulting body of ice constitutes a *pied-mont glacier* (Fig. 193). Piedmont glaciers are confined to high latitudes. In some cases the snow-field that gives rise to a glacier is restricted to a relatively small depression in the side of a mountain, or in the escarpment of a plateau. In such cases the snow-field and glacier are hardly distinguishable, and the latter descends but little below the snow-line. Such a glacier, nestled in the face of a cliff, has been called a *cliff glacier*¹ (Fig. 194). Cliff glaciers are often as wide as long, and are always small, and between them

¹ Jour. of Geol., Vol. III, p. 888.



Fig. 189.— End of Bryant glacier, a high-latitude glacier of North Greenland.



Fig. 190.— The Rhone glacier. (Photo. by Reid.)

and valleys glaciers there are all gradations (Fig. 195). Occasionally the end of a valley glacier, or the edge of an ice-sheet, reaches a precipitous cliff, and the end or edge of the ice breaks off and



Fig. 191.— The medial moraine of the Roseg Glacier, Switzerland.

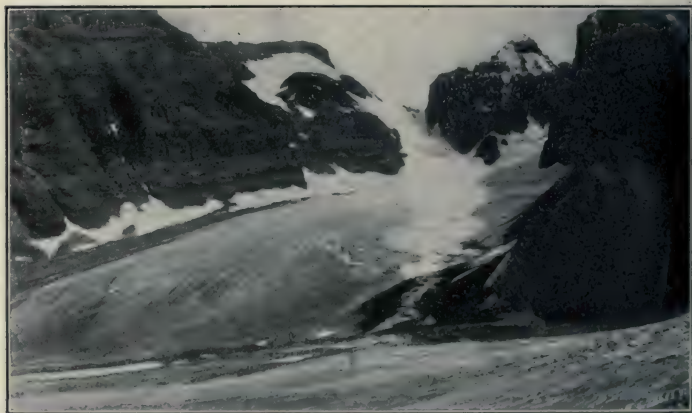


Fig. 192.— Lefroy Glacier and its junction with Victoria Glacier. Lake Louise, Canadian Rockies.

accumulates like talus below. The fragments of ice may then become a coherent mass by regelation, and the whole may resume

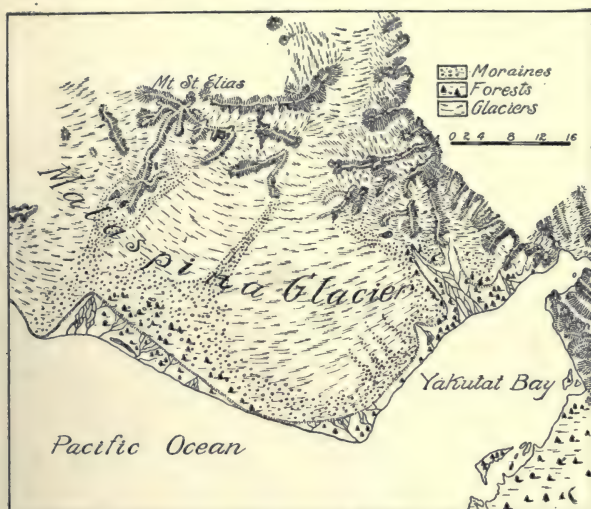


Fig. 193.—Malaspina Glacier, a Piedmont glacier in Alaska. (After Russell.)



Fig. 194.—A cliff glacier, coast of North Greenland. The height of the cliff is perhaps 2,000 feet. The water in the foreground is the sea.

motion. Such a glacier is called a *reconstructed glacier*. The precipitous cliffs of the Greenland coast furnish illustrations.

Of the foregoing types of glaciers, ice-caps far exceed all others both in size and importance, while valley glaciers outrank the remaining types; but since the valley glaciers are the most familiar, the general phenomena of glaciers will be discussed with primary reference to them.

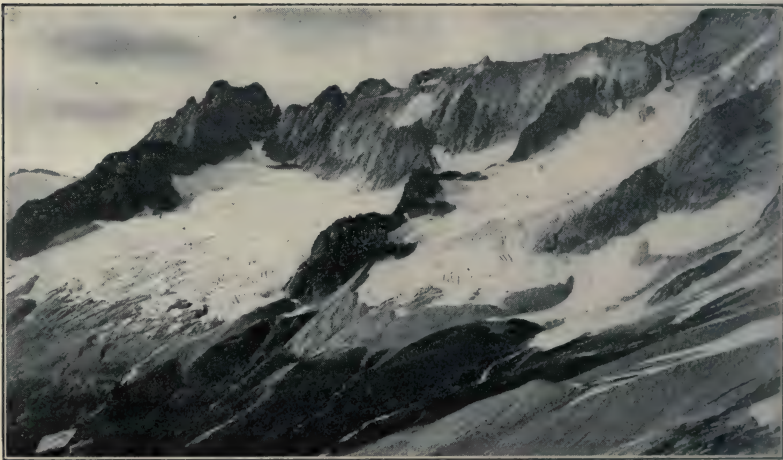


Fig. 195.—Glaciers intermediate in type between a cliff glacier and a valley glacier. Cascade Mountains, Wash. (Willis, U. S. Geol. Surv.)

General Phenomena of Glaciers¹

Dimensions. Valley glaciers sometimes occupy only the upper parts of mountain valleys, sometimes extend through them, and

¹The following list includes many of the more available articles and treatises on existing glaciers; others are referred to in the following pages.

Alaskan glaciers: Reid, (1) Nat. Geog. Mag., Vol. IV, pp. 19-55; (2) Sixteenth Ann. Rept., U. S. Geol. Surv., Part I, pp. 421-461. Russell, (1) Nat. Geog. Mag., Vol. III, pp. 176-188; (2) Jour. of Geol., Vol. I, pp. 219-245.

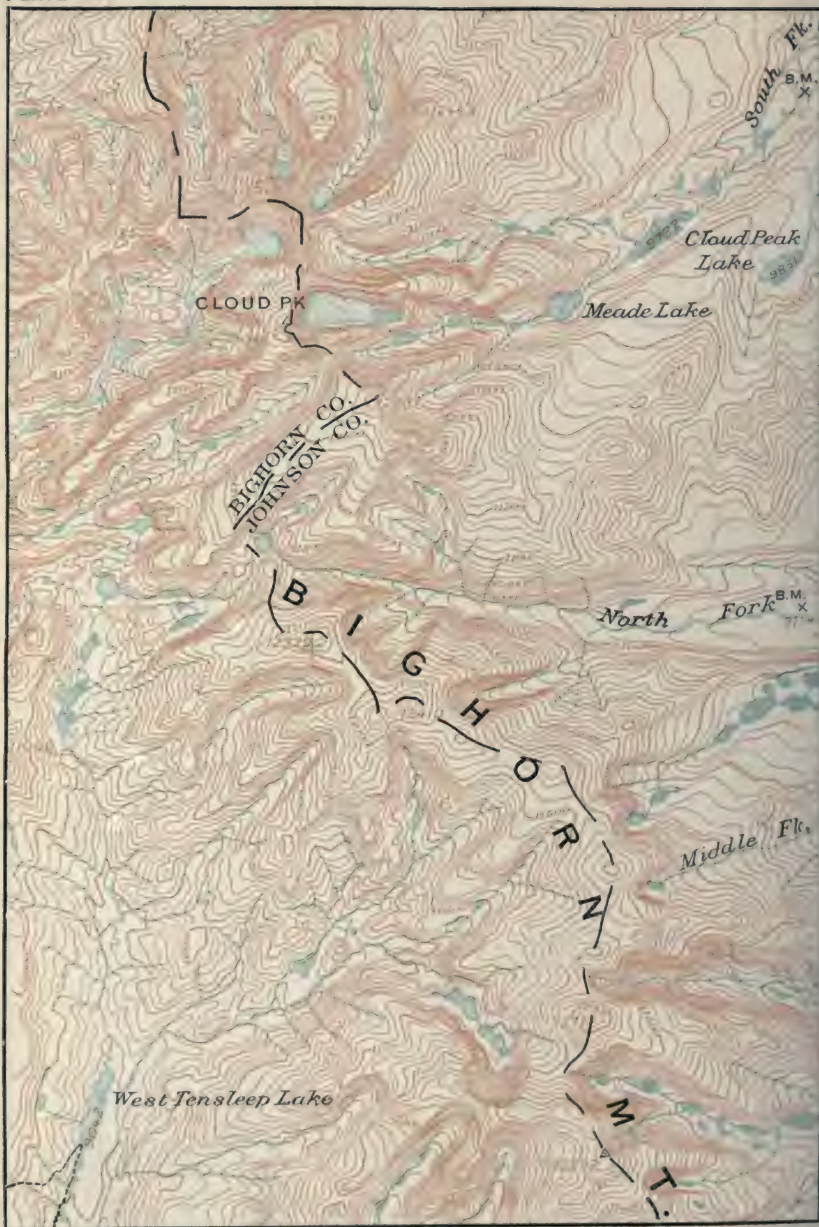
Glaciers in the United States: (1) Russell, Eighteenth Ann. Rept., U. S. Geol. Surv., Part II, pp. 379-409; (2) Glaciers of North America.

Greenland glaciers: Chamberlin, Jour. of Geol., Vol. II, pp. 768-788; Vol. III, pp. 61-69, 198-218, 469-480, 565-582, 668-681, and 833-843; Vol. IV, pp. 582-592. Salisbury, Jour. of Geol., Vol. IV, pp. 769-810.

General: Shaler and Davis, Illustrations of the Earth's Surface.



Glaciers on Glacier Peak, Washington. Scale, about 2 miles per inch.
(Glacier Peak Sheet, U. S. Geol. Surv.)



A portion of the Bighorn Mountains, showing glaciated valleys, the heads of which are in many cases cirques. Scale, about 2 miles per inch. (Cloud Peak, Wyo., Sheet, U. S. Geol. Surv.)

sometimes push out on the plain beyond. In length they range from a fraction of a mile to many miles. Their thickness is usually measured by scores or hundreds of feet rather than by denominations of a larger order, but the variation is great, and exact measurements are almost wholly wanting. The minimum thickness is that necessary to cause movement, and this varies with the slope, the temperature, and other conditions. There is also much variation in the thickness in different parts of the same glacier. As a rule, it is thinnest in its terminal portion, and thickest at some point between its terminus and its source. Cliff and reconstructed glaciers are comparable in size to the smaller valley glaciers. Piedmont glaciers may attain greater size. An ice-cap is thickest, theoretically, at its center, and thins away to its borders, but its actual dimensions are influenced by the topography of the surface on which it is developed. The Greenland ice-cap rises about 9,000 feet above the sea toward its southern end, and it probably rises higher in the unexplored center of the broader part of the island. The height of the rock surface beneath the ice is unknown, but it is unlikely that it averages half this amount, and hence the ice is probably very thick in the center. The ice cap of Antarctica appears to rest on high land; its thickness is unknown.

Limits. The ice of a glacier is always moving forward, but the *end* of a glacier may be retreating, advancing, or remaining stationary, according as the wastage exceeds, falls short of, or equals the forward movement. The position of the lower end of a glacier is therefore determined by the ratio of movement to wastage. Its upper end is generally ill-defined. In a superficial sense, it is the point where the ice emerges from the snow-field; but the lower limit of the snow-field is often ill-defined, and in any case is not the true upper limit of the glacier. The snow-field is really an ice-field, covered with snow, and there is movement from it to the tongue of ice in the valley. The ice so moving is, in reality, a part of the glacier.

The lower end of a glacier is usually free from snow and *névé* in summer, but toward its upper end it is covered with *névé*, then with snow, and finally merges into the snow-field without having ceased to be a glacier. The term glacier is, however, commonly

used to mean merely the more solid portion outside (below) the snow-field.

Movement. The advance of a glacier is too slow, as a rule, to be seen from day to day, and must be detected in other ways. If its end advances, it may override or overturn objects in front of it, or it may move out over ground previously unoccupied. But even when the end of a glacier is not advancing, the movement of the ice may be established by means of stakes or other marks set on its surface. If the positions of these marks, relative to fixed points on the sides of the valley, is determined, they are found after a time to have moved down the valley. Rows of stakes or lines of stones set across a glacier in its upper, middle and lower portions have revealed many facts concerning the movement of the ice.

Generally speaking, the middle of a valley glacier moves more rapidly than its sides, and its top more rapidly than its bottom. In Switzerland, where the glaciers have been studied more carefully than elsewhere, the determined rates of movement range from one or two inches to four feet or more per day. Some of the larger glaciers in other regions move more rapidly, but it does not follow that large glaciers always move faster than small ones. The Muir glacier of Alaska has been found to move some seven feet per day,¹ and some of the glaciers of Greenland have been found to move, in the summer time, 50 or 60 feet per day; but these rates have been observed only where the ice of a large inland area crowds down into a comparatively narrow fiord, and debouches into the sea, and then only in the summer. In the case of the glacier with the highest recorded rate of summer movement, 100 feet per day, the advance was only 34 feet at about the same place in April. The average movement of the border of the inland ice of Greenland is very small, probably less than a foot a week.

Conditions affecting rate of movement. The rate of glacier movement appears to depend on (1) the depth of the moving ice, (2) the slope of the surface over which it moves, (3) the slope of the upper surface of the ice, (4) the topography of its bed, (5) temperature, and (6) the amount of water in the ice. Great thickness,

¹ Reid. Natl. Geog. Mag., Vol. IV, p. 44.

steep slopes, smoothness of bed, a high (for ice) temperature, and abundance of water favor rapid movement. Since some of these conditions, notably temperature and amount of water, vary with the season, the rate of movement of a glacier varies during the year. Other conditions, especially the first of those mentioned above, vary through longer periods of time, and cause corresponding variations in the rate of movement.

A declining upper surface is essential to glacier motion. There are short stretches where this is not the case, and indeed there are occasional places where the upper surface slopes backward, as where the ice is pushed up over a swell in its bed; but such cases are local exceptions, and do not militate against the general truth of the statement that the upper surface of a glacier declines in the direction of motion. A declining *lower* surface is less necessary. In the case of valley glaciers, the bed does, as a rule, decline in the direction of motion; but that there are exceptions is shown by the deep basins in rock which such glaciers often leave behind them when they retreat. In the great continental glaciers of recent geologic times, the ice frequently moved up slopes for scores, and even hundreds of miles; but in all such cases, the prevailing slope of the *upper surface* must have been *down* in the direction of movement.

Fluctuations of glaciers. Observation has shown that the lower ends of glaciers advance and retreat at intervals,¹ and that the periods of advance follow a succession of years when the snowfall has been heavy and the temperature low, while the periods of retreat follow a succession of years when the snowfall has been light and the temperature above the average. The periods of advance and retreat lag behind the periods of heavy and light snowfall respectively, by some years, and a long glacier responds less promptly than a short one.

Likenesses and unlikenesses of glaciers and rivers. Slope, roughness of bed, and volume affect the movement of glaciers somewhat as they affect the movement of rivers. The temperature of

¹ Reid. Variations of Glaciers. Jour. of Geol., Vols. III, p. 278; V, p. 378; VI, p. 473; VII, p. 217; VIII, p. 154; IX, p. 250; X, p. 313; XI, p. 285; XIII, p. 313; XIV, p. 402; and XV, pp. 46 and 664.

water, on the other hand, has little effect on the flow of a river so long as it remains unfrozen; but the effect of temperature on the motion of ice is important. In many cases, indeed, the temperature,

together with the water that is incidental to it, seems to be the chief factor in determining the rate of movement. The way in which its effects are felt will be discussed later.

From Fig. 196 it will be seen that a valley glacier is an elongate body of ice, following the curves of the valley in stream-like fashion. It has its origin in the snows collected on the mountain heights, and it works its way down the valley in a manner which, in the aggregate, is similar to the movement of a stiff liquid. The likeness to a river extends to many details. Not only does the center move faster than the sides, and the upper part faster than the bottom, as in the case of streams, but the movement is more rapid in narrow parts of the valley and



Fig. 196.—Aletsch Glacier, Switzerland.

slower in the broader parts. These and other likenesses, some of which are apparent rather than real, have given rise to the view that glacier ice moves like a stiff viscous liquid.

But while the points of likeness between glaciers and rivers are several, their differences are at least equally numerous and significant. Though the trains of debris on the surface (the dark bands in Fig. 196) pass nearer the projecting points of the valley walls and farther from the receding bends like the central currents of streams, they do not conform in detail to the course of the winding

valley, nor is there evidence of rotatory motion, as in the water of a river. Furthermore, the glacier is readily fractured, as the numerous gaping crevices on many glaciers show. The crevasses are sometimes longitudinal, sometimes transverse, and sometimes



Fig. 197.—Takakrow Falls, Yoho Valley, British Columbia. The glacier above feeds the stream which falls. (Detroit Photographic Company.)

oblique. In the case of arctic glaciers, longitudinal crevassing is especially conspicuous. *Crevasses* appear to be developed wherever there is appreciable tension, and the causes of tension are many. An obvious cause is an abrupt increase of gradient in the bed (Fig. 198). If the change of gradient is considerable, an ice-fall or cascade results, and the ice may be greatly riven. Transverse crevasses

at the margin sometimes appear to be the result of the tension developed on a curve. Oblique crevasses on the surface near the sides are commonly ascribed to the tension between the faster-moving center and the slower-moving margins, and in like manner cracks that rise obliquely from the bottoms are attributed to the tension between the faster-moving parts above and the slower-moving parts below. All these crevasses indicate strains to which a liquid, whose pressures are equal in all directions, does not offer

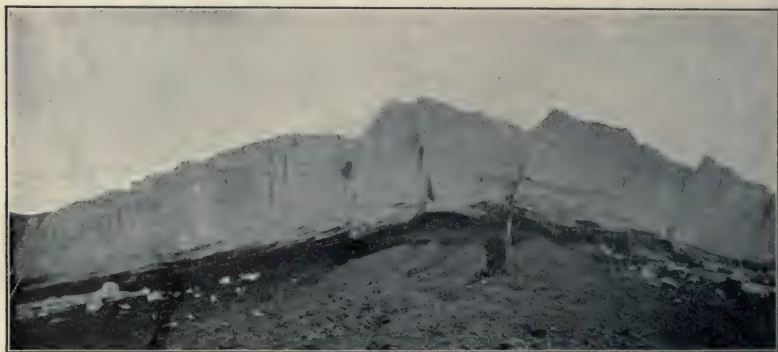


Fig. 198.—Crevassed glacier, the cracking due to change in grade of bed. North Greenland.

a close analogy. Longitudinal crevasses may affect both the narrow part of a glacier and its deploying end, and are the result of tension developed by movement within the ice itself, to which, again, rivers offer no analogy. All cracks show that the glacier is a very brittle body, incapable of resisting even very moderate strains brought to bear upon it very slowly. In its behavior under tension, therefore, a glacier is notably unlike a river.

Surface moraines. The surface of a glacier is often affected by rock debris, which is sometimes disposed in the form of belts or *moraines* (Fig. 199). The surface moraines may be *lateral*, *medial*, or *terminal*. A *lateral moraine* is any considerable accumulation of debris in a belt on the side of a glacier. A *medial moraine* is a similar accumulation at some distance from the margins, but not necessarily in or even near the middle. There may be several medial

moraines on one glacier, in which case some of them may be far from the center. In valley glaciers, the *surface terminal* moraine often connects two lateral moraines, making a loop roughly concentric with the end of the glacier.

Besides the surface moraines, there may be scattered boulders and bits of rock of various sizes on the ice, and, in addition to the

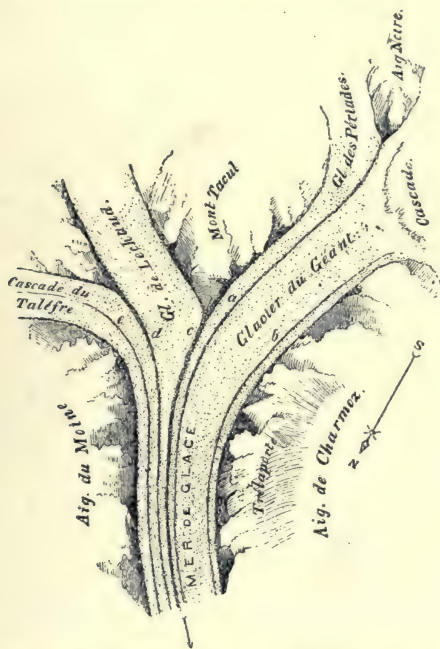


Fig. 199.—Figure showing the union of glaciers and the development of medial moraines by the union; also the position of lateral moraines. (After Tyndall.)

coarse material, there is often some dust which has been blown upon the ice.

Relief due to surface debris. The debris on the ice affects its topography by influencing the melting of the ice beneath and about it. The rock debris absorbs heat more readily than the ice. A thin piece of stone lying on the ice is warmed through by the sun's rays, and, melting the ice beneath, sinks, just as a piece of black

cloth on snow will sink because of the increased melting beneath it. Though a good absorber of heat, rock is a poor conductor, and so the lower surface of a thick mass of stone is not warmed notably, and the ice beneath, being protected from the sun, is melted more slowly than that around it. The result is that the boulder presently



Fig. 200.— A glacial table due to the protection of the ice beneath the flat stone from the rays of the sun. Talèfre Glacier.

stands on a protuberance of ice (Fig. 200). When its pedestal becomes high, the oblique rays of the sun and the warm air surrounding it cause it to waste away, and the capping boulder falls.

The same principles apply to the moraines. A surface moraine usually protects the ice beneath from melting, and causes the development of a ridge of ice beneath itself. As the ice on either side is lowered by ablation, the moraine matter tends to slide down

on either hand. So far does this spreading go, that in some cases the lower end of a glacier is completely covered with the debris which has spread from the medial and lateral moraines.

Debris below the surface. The lower part of a glacier, as well as the upper, carries rock debris. This debris is sometimes so abundant, especially near the ends and edges of the ice, that it is difficult

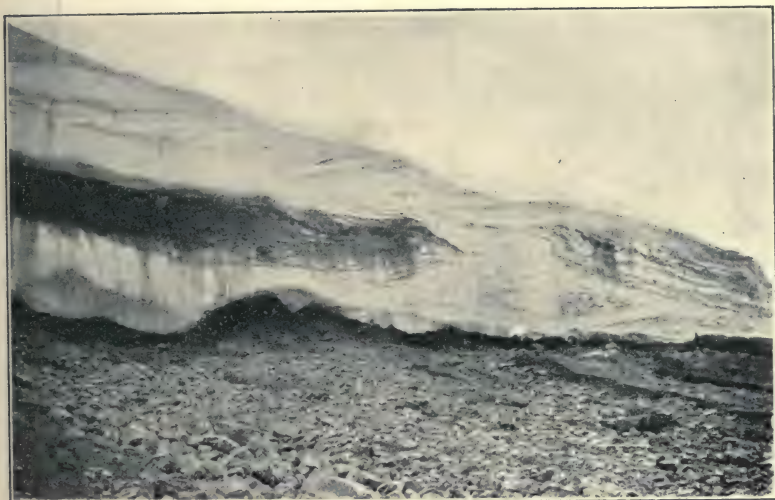


Fig. 201.—Side view of end of glacier. Southeast side of McCormick Bay, North Greenland. Shows structure of ice as well as position of debris.

to locate the bottom of the glacier; for between the moving ice which is full of debris, and the stationary debris which is full of ice, there seems to be a nearly complete gradation. The debris in the lower part of arctic glaciers, and to some extent of others, is often disposed in thin sheets sandwiched in between layers of clean ice. Debris also occurs to some extent in the ice far above its base, sometimes in sheets and sometimes in bunches. These various relations are illustrated by Figs. 201 and 202.

Temperature

In winter, the surface of the ice becomes as cold as the air above it, and the cold of the surface penetrates downward. This

descent of the surface cold may be called the *winter wave* of low temperature. The degree of cold becomes rapidly less below the surface, and at no great depth the temperature is not much affected

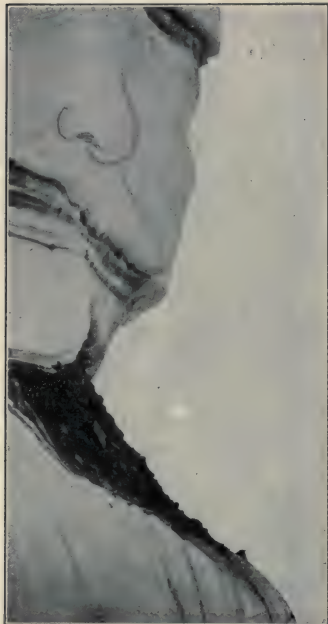


Fig. 202.—A part of the vertical side of a North Greenland glacier. The vertical even overhanging faces are sometimes more than 100 feet high.

by the seasons. In middle latitudes, the zone of no seasonal variation of temperature on land is only 50 or 60 feet below the soil. Its depth in ice is not known, but it is not probable that the cold of winter has much effect below a similar depth. Conduction alone considered, the temperature of the ice at the depth where the cold wave dies out, should correspond, approximately, to the mean annual temperature of the region, provided that temperature is below the melting-point of ice. At this depth, the temperature of the ice in middle Greenland should be about 20° Fahr.—the mean annual temperature of the region.

With the coming of summer, the temperature of the surface of the ice may be raised to 32°, and this relatively high temperature makes itself felt below the surface as the *warm wave*, if the temperature of ice can ever be said to be warm. The relatively high temperature of the

surface makes itself felt below both by conduction and by the descent of water. The former affects the ice at all temperatures, the latter only after the melting-point of the ice at the surface is reached. The first conforms measurably to the warm wave affecting other solid earth-matter, while the second is governed by other laws. After the surface portion of the ice is brought to the melting temperature, the additional heat which it receives melts ice, and is transformed from *sensible* into *potential* heat. Ice charged

with water is *potentially*, but not *sensibly*, warmer than ice which has just reached the melting temperature. The warm wave of conduction dies out below, like the cold wave. The warm wave descending by the flow of water stops where the freezing temperature of water is reached, except where crevasses extend to greater depths.

The foregoing considerations warrant the generalization that glaciers normally consist of two zones (1) an outer or upper zone of varying temperature, and (2) an under zone of nearly constant temperature. The under zone obviously does not exist where the thickness of the ice is less than the thickness of the zone of fluctuating temperature, as may be the case in very thin glaciers and in the thin ends and edges of all glaciers.

The temperature of the bottom. The internal heat of the earth is slowly conducted to the base of a glacier where it melts the ice at the estimated average rate of about one-fourth of an inch per year. It is probable that in all thick glaciers the temperature of the bottom is constantly at the melting-point. In glaciers or in parts of glaciers so thin as to lie wholly within the zone of fluctuating temperature, the temperature of the bottom is obviously not constant.

Temperature of the interior of the ice. The variation of temperature of the surface of a glacier has already been stated to lie between a maximum of 32° Fahr. and the minimum temperature of the region where the glacier occurs. In the zone of varying temperature, the variation is less and less with increasing depth. In the zone of constant temperature, the range is from the mean annual temperature of the region at the top of the zone (provided this is not above the melting-point of ice at this depth) to the melting temperature of the ice at the bottom. Within these limits the range may be great or slight.

Considering only the effects of the external seasonal temperatures and the internal heat of the earth, it appears that all the ice in the zone of constant temperature in the lower end of a typical alpine glacier should have a melting temperature constantly, for the average annual temperature of regions where the ends of such glaciers occur is usually above 32° Fahr., and this determines a temperature of 32° Fahr., approximately, at the top of the zone,

while a melting temperature is maintained at the bottom by the earth's interior heat. In thin glaciers of very cold regions, the low temperature descending from the surface may so far overcome the effect of internal heat as to keep the bottom of the ice at a freezing temperature during the winter season; but in all other cases the ice at the bottom of the under zone probably has a melting temperature, while that above is probably colder, except where the ice is warmed by the descent of surface water.

In the higher altitudes and in the polar latitudes, where glaciers are chiefly generated, the mean annual temperature of the surface is usually below the melting-point of ice. Here the temperature of the ice between the top and bottom of the zone of constant temperature must be below the melting-point, on the average, unless *heat enough is generated in the interior of the ice* to offset the effect of the temperature above. For example, where the mean annual temperature is 20° Fahr. or lower, as in middle Greenland, the mean temperature in the zone of constant temperature should range from 20° Fahr. at the top, to 32° Fahr. (or a little less) below; i. e., it should average some 6° below the melting-point, disregarding the effect of water descending from the surface. Under these conditions, all the ice in the zone of constant temperature, except that at its bottom, must be permanently below the melting-point; but it is worthy of especial note that much of it *is but little below*. In alpine glaciers, the part of the ice affected by this constant low temperature (below freezing) is presumed to be chiefly that which lies beneath the snow-fields. In polar glaciers, the low temperature probably prevails beneath the surface not only throughout the great ice-caps, but also in the marginal glaciers which descend from them.

From these theoretical considerations we may deduce the generalization that in the zone of constant temperature *within the area of glacier growth* the temperature of the ice is generally *below* the melting-point, while *within the area of wastage* the temperature of the corresponding zone is generally *at* the melting-point.

Compression and friction as causes of heat. The foregoing conclusions are somewhat modified by dynamic sources of heat. Both the compression arising from gravity, and the friction developed

where there is motion, are causes of heat. Since friction occurs only when motion takes place, the heat which it generates is secondary and may, for present purposes, be neglected. But *compression produces heat at the point of compression, and also lowers the melting-point slightly*. If the compression is considerable in ice which is already near the melting temperature, the granules may be warmed to the melting-point where they press each other. In this case melting will take place at the points of compression, and the water so produced will flow to points of less pressure, and be re-frozen immediately. Melting at the points of compression would result in some yielding of the mass, and in some shifting of the pressure to new points, where compression and melting would again take place. From considerations already adduced, it appears that the temperature in some parts of every considerable body of ice must be such as to permit these changes. The heat due to compression and friction may modify the theoretical conclusions deduced above.

Summary. If the foregoing generalizations are correct, (1) the surface of a glacier is likely to be melted during the summer; (2) its immediate bottom is slowly melting all the time (unless the thickness of the ice is less than the thickness of the zone of annual variation); (3) its sub-surface portion *in the zone of waste* is generally melting, owing to descending water, compression, and friction; while (4) its sub-surface portion *in the zone of growth* is probably below the melting-point except as locally brought to that temperature by compression, friction, descending water, and, at the bottom, by conduction from the rock beneath.

Glacier motion is not under discussion at this point, but it may be pointed out that since there must be motion in the area of growth in order to supply the loss in the area of waste, the *fundamental* cause of motion must be operative in bodies of ice whose mean temperature is below the melting-point, unless the dynamic sources of heat are considerable.

Drainage. Some of the water produced by surface melting forms little streams on the ice. Sooner or later they plunge into crevasses or over the sides and ends of the glacier. In the former case, they may melt or wear out well-like passages (*moulins*) in the ice, and even in the rock beneath. Much of the surface water sinks

into the ice. The depth to which it penetrates is undetermined by observation, but it doubtless goes down to the zone of constant temperature in all cases, and still lower in some cases, as where there are crevasses, and where the temperature is as high as 32° Fahr. all the way to the bottom. At considerable distances above the line of perennial snow there is little water either from melting or from rain, and hence relatively slight penetration. Below the line of perennial snow, and for a short distance above it, there is more melting and rain, and here it is probable that the water often penetrates to the bottom of the ice during the melting season, even independently of crevasses.

Once within the glacier, the course of the water is variable. Exceptionally it follows definite englacial channels, as shown by springs or streams issuing from the ice at some point above its bottom. Oftener it descends or moves forward through the irregular openings which the accidents of motion have developed. If it reaches a level where the temperature is below its freezing-point, it congeals. Otherwise it remains in cavities or descends to the bottom. The water produced by melting within the glacier probably follows a similar course. So far as these waters descend to the bottom, they join those produced by basal melting, and issue from the glacier with them. In alpine glaciers, the waters beneath the ice often unite in a common stream in the axis of the valley, and hollow out a tunnel. Thus the Rhone River is already a considerable stream where it issues from beneath the Rhone Glacier. In the glaciers of high latitudes, subglacial tunnels are less common, and the drainage is in streams along the sides of the glaciers or through the debris beneath and about them.

At the end of the glacier, all waters, whether they have been superglacial, englacial, or subglacial, unite to bear away the silt, sand, gravel, and even small boulders set free from the ice, and to spread them in belts along the border of the ice, or in trains stretching down the valleys below, forming *glacio-fluvial* deposits.

THE WORK OF GLACIERS

Erosion and Transportation

Glaciers abrade the valleys through which they pass, carry forward the material which they remove from the surface, and wear, grind, and ultimately deposit it. Like other agents of gradation, therefore, their work includes erosion, transportation, and deposition.

Getting load. If the snow-field which is to become a glacier accumulates on a rough surface covered with abundant rock debris, the glacier already has a basal load when it begins to move, for the snow covers, surrounds, and includes such loose blocks of rock as project above the general surface, and envelops all projecting points of rock within its field. When the ice begins to move, it carries forward this loose rock in its bottom, and tears off the weak points of the enveloped rock-projections. It may also drag along some of the earthy matter of the surface on which the ice forms, and to which the ice is frozen. In addition to the *basal* and *sub-glacial* load which the glacier has at the outset, there may be surface debris which has fallen on the snow or ice from cliffs above. This is likely to be the case where steep cliffs tower above the snow-fields. If debris descending to the glacier in this way is unburied, it is *superglacial*, but if it has been buried by subsequent falls of snow, it is *englacial*.

Once in movement, the ice not only moves the debris to which it was originally attached, but it gathers new load. This it acquires partly by the rasping effect of its rock-shod bottom, and partly by its power of plucking off or quarrying out considerable blocks of rock from its sides and bottom. This plucking process is at its best where the ice passes over the cliffs of jointed rock, but is not confined to such situations. The steep bed of a valley glacier is often worn more by plucking than by rasping. The advancing ice gets some material, too, especially loose debris, by freezing to it, for the frozen water in the soil, etc., becomes continuous with the ice above, and the two move together. Superglacial material may be acquired during movement, as well as before it, by the fall of debris from cliffs, or by the descent of avalanches.

Conditions influencing rate of erosion. (1) A somewhat obstructive configuration of the surface over which the ice moves is necessary for effective erosion. Ice wears a flat surface relatively little since there is little for it to get hold of. Ice sometimes overrides such a surface, burying its soil and even more or less of its herbaceous vegetation. Erosion is probably at its maximum, so far as influenced by topography, when the surface is rough enough to offer



Fig. 203.— Striæ on bed-rock. Kingston, Des Moines County, Ia.

notable catchment for the base of the ice, but not so rough as to impede its motion seriously. The amount of roughness favorable for the greatest erosion increases with increasing thickness of the ice.

Other conditions which influence erosion by ice are (2) the amount of loose or slightly attached debris on the surface; (3) the resistance of the rock; (4) the slope of the surface; (5) the thickness of the ice; (6) the rate of its movement; and (7) the abundance and character of the debris which it has to work with. The effect of most of these conditions is evident, but the effect of the last is less simple. Clean ice passing over a smooth surface of solid rock would have little effect upon it; but a rock-shod glacier

will abrade the same surface notably. The effect of this abrasion is shown in the grooves and scratches (*striæ*) which the stones in



Fig. 204.—*Striæ*, grooves, etc., in a canyon tributary to Big Cottonwood Canyon, Wasatch Mountains. (Church.)

the bottom of the ice inflict on the surface of the rock over which they pass (Figs. 203 and 204). At the same time, the stones in the ice are themselves worn both by abrasion with the bottom, and



Fig. 205.—Stones striated by glacial wear.

with one another (Fig. 205). It does not follow, however, that erosion is greatest when there is most material in the bottom of the ice; for with increase of debris there may be decrease of motion,¹ and decrease of motion interferes seriously with the efficiency of erosion. When any considerable thickness of ice at the bottom of a glacier is full of debris, the loaded portion may approach stagnancy, while the cleaner ice above shears over it. A moderate but not excessive load of debris is, therefore, favorable for great erosion. Something depends, too, on the character of the load. Coarse, hard, and angular debris is a more effective instrument of abrasion than fine, soft, or rounded material. So far as plucking is concerned, rate of motion is probably more important than load. Other things being equal, ice which is unyielding, as when full of debris, would be more effective in plucking than ice which is more yielding.

In connection with the resistance of the rock, it should be noted that resistance is not a matter of hardness and softness simply. Rock which is affected by cleavage planes, whether joints or bedding planes or both, is subject to erosion by plucking, as well as by the abrasion effected by the load in the bottom of the ice. On steep slopes, plucking is probably more important, on the whole, than wear by the debris carried.

So far as concerns the ice itself, erosion is not most effective at the end of a valley glacier, or at the edge of an ice sheet, for here the strength of movement is too slight and the load too great; nor is the most effective erosion at the source or near it, for though the ice here may be thick, the movement is slow and the load likely to be slight. Ice alone considered, erosion is most effective somewhere between the source and the terminus of a glacier, and probably much nearer the latter than the former. The conditions of the surface over which the ice passes may be such as to make the place of greatest erosion vary widely.

Summary. In summary it may be said that rapidly moving ice of sufficient thickness to be working under goodly pressure, shod with a sufficient but not excessive quantity of hard-rock material, passing over non-resistant formations possessing a topog-

¹ Russell. Jour. of Geol., Vol. III, p. 823.

raphy of sufficient relief to offer some resistance, and yet too little to retard the progress of the ice seriously, will erode most effectively.

Varied nature of glacial debris. From its mode of erosion it will be seen that a glacier may be charged with various sorts of material.



Fig. 206.— A mountain valley in the Wasatch Mountains, not glaciated.
(Photo. by Church.)

At its bottom there may be (1) boulders which the ice has picked up from the surface, or which it has broken off from projecting



Fig. 207.— A mountain valley which has been strongly glaciated, Wasatch Mountains. (Photo. by Church.)

points of rock over which it has passed; (2) smaller pieces of rock of the size of cobbles, pebbles, etc., either picked up by the ice from its bed or broken off from larger masses; (3) the fine products (rock-flour) produced by the grinding of the debris in the ice on the rock-bed over which it passes, and similar products resulting from the rubbing of stones in the ice against one another; and (4) sand, clay, soil, vegetation, etc., derived from the surface overridden. Thus the materials which the ice carries (called *drift*) are of all



Fig. 208.— Figure showing contrast between a glaciated rock surface below, and non-glaciated crests above. Kearsarge Pinnacles, Bubbs Creek Canyon, Cal.

grades of coarseness and fineness, from huge boulders to fine clay. The coarser materials may be angular or round at the outset, and their forms may be changed and their surfaces striated as they are moved forward. Whether one sort of material or another predominates depends primarily on the nature of the surface overridden.

The topographic effects of glacial erosion. In passing through its valley, an alpine glacier deepens it, widens its lower part, and smooths its slopes up to the limit of the ice. It tends to make a V-shaped valley (Fig. 206) U-shaped (Fig. 207). The change in topography at the upper limit of glaciation is often marked (Fig. 208).

The deepening of a valley by glacial erosion may throw its

tributaries out of topographic adjustment. Thus if a main valley is lowered 100 feet by glacial erosion while its tributary is not deepened, the lower end of the latter will be 100 feet above the



Fig. 209.— A hanging valley near Lake Kootenay. (Photo, by Atwood.)

former when the ice disappears. Such a valley is called a *hanging valley* (Fig. 209). Such valleys are common in regions which were recently glaciated, like the western mountains of North America.



Fig. 210.— Diagram representing a hill unworn by ice, and the irregular contact of soil and rock.



Fig. 211.— Diagram showing the effect of glacial wear on a hill such as is shown in Fig. 210.

Ice-caps which overspread the surface irrespective of valleys and hills tend to reduce the angularities of the surface. Hills and ridges are cut down and smoothed (Figs. 210 and 211); but since

valleys parallel to the direction of movement are deepened at the same time, it is doubtful if the relief of the surface is commonly reduced by the erosion of an ice-cap.

Fiords. A glacier descending into the head of a bay may gouge it out to a very considerable depth, and cause its head to advance into the land. When the ice finally melts, the bay, if narrow, deep, and long, with high slopes, is called a *fiord*. Many of the fiords of coasts in high latitudes have arisen in this way, and some of the glaciers of these coasts are now making fiords. Fiords arise in other ways also.

The positions in which debris is carried. As a result of the methods by which a glacier gets its load, debris is carried in three positions: (1) the *basal* or *subglacial*, (2) the *englacial*, and (3) the *superglacial*. The material picked up or rubbed off from the surface over which the ice moves is normally carried forward in the bottom of the ice, and is therefore basal; that which falls on the surface is usually carried on the surface, and is therefore superglacial. Either basal or superglacial drift may become englacial, as we shall see.

The basal load of a glacier is constantly being mixed with new accessions derived from ground over which the ice is passing, and this admixture tells the story of the work done by the bottom of the ice. The superglacial material, on the other hand, is normally borne from the place of origin to the place of deposition without such intermixture. It is doubtful if much debris is moved along beneath (that is, strictly below the bottom of) the ice, though the movement of the ice would tend to drag along the loose material of its bed. If drift were carried forward in such position, it would be strictly *subglacial*.

Transfers of load. While the origin of the load usually determines its position at the outset, exceptions and complications arise from the transfer of load from one position to another, and from the gradation of one horizon to another.

Most of the debris gathered by ice is acquired at its bottom. While such material is basal *at the outset*, some of it may find itself above the bottom a little later. Thus when ice passes over a hill, the bottom of the ice rends debris from its top. To the lee of

the hill the ice from either side may close in under that which came over the top. The debris derived from the top of the hill by the bottom of the overriding ice will then be well up in the ice. It has passed from an initial basal to a subsequent englacial position; but the change does not usually involve an actual rise of the material. If carried upward at all, the upward movement is temporary only, and incident to the passage of the ice up over the hill, or to other local causes.

Superglacial debris may obviously become englacial by falling into crevasses or by being carried down by descending waters, and either superglacial or englacial debris may become basal by the same means. There is less ice-free land in immediate association with ice-caps than with valley glaciers, and the ice-free land about the borders of an ice-cap is less likely to be in the form of cliffs above it. Except at their edges where the ice is thin, the surfaces of ice-caps are comparatively clean, for there is little land which rises above them in such position as to furnish surface debris.

Englacial material may become superglacial by surface ablation. In this case the drift does not rise, but melting brings the surface of the ice down to it. This occurs chiefly at the end or edge of the ice, where the surface melting is greatest. Englacial material plucked or rasped from an elevation over which the ice has passed is liable to be disposed in a longitudinal belt in the ice in the lee of the elevation itself. By surface ablation this material may reach the surface at some point below its source (Fig. 212), and be disposed as a

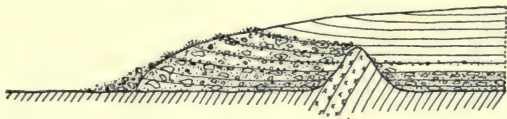


Fig. 212.—Diagram illustrating one way in which a glacier gets englacial material. •

medial moraine. Such a moraine has an origin very different from that of a medial moraine formed by the junction of two lateral moraines of superglacial origin. Englacial debris, especially that near the bottom, may also become basal by the melting of the bottom of the ice.

Drift is sometimes transferred from a basal to an englacial and then to a superglacial position, by upward movement. Such transfer is the more remarkable because the specific gravity of rock is two and a half to three times that of ice, so that the normal tendency of rock is to sink in ice.

In arctic glaciers, and probably in others, some material which has been basal becomes englacial by being sheared forward over



Fig. 213.— Taking debris from a protuberance of the bed.

ice in front of it. So far as observed, this takes place chiefly where the ice in front of the plane of shearing lies at a lower level than that behind, as where the surface of an upland falls off into a valley, or where a boss of rock shelters the ice in its lee from the thrust of the overriding ice (Fig. 213).

At the borders of arctic glaciers the lower layers are not infrequently turned up, as shown in Fig. 214. Where the layers turn up at the end of a glacier, basal and englacial debris is carried to the surface by actual upward movement, and a terminal moraine or a series of terminal moraines is sometimes aggregated *where the*

upturned layers of ice outcrop at the surface (Fig. 215). That the material of these moraines was originally basal is abundantly demonstrated in many cases by the bruised and scratched condition

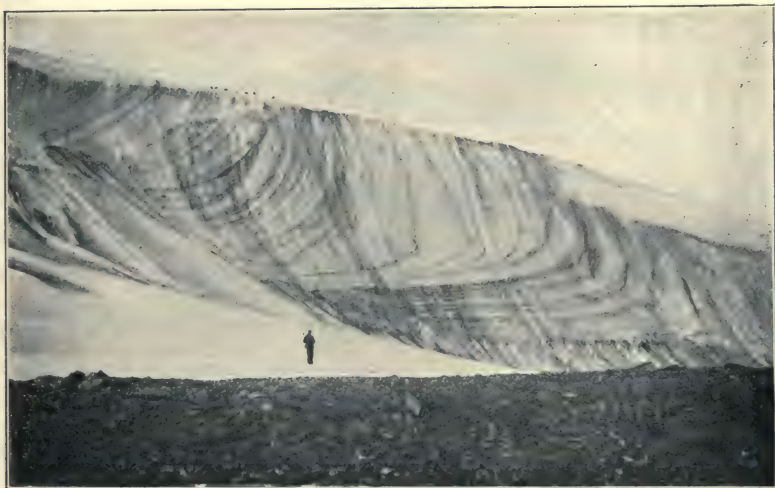


Fig. 214.— End of a North Greenland glacier, showing the upturning of the layers of ice at the end. This structure is common in North Greenland. At one point, a few stones are seen on the surface of the ice where an upturned layer comes to the surface.

of the boulders and pebbles, and sometimes by the nature of the material itself. The upturning sometimes affects the edges of

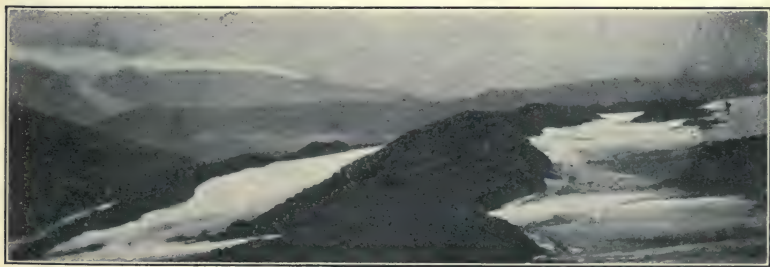


Fig. 215.— Surface terminal moraines due to upturning. Edge of the ice-sheet, North Greenland.

glaciers (Fig. 216) as well as their ends, and the material thus brought to the surface gives rise to lateral moraines. Sometimes also there is an upturning of the ice along a longitudinal zone well back from the lateral margins (Fig. 216), and the material so borne to the surface in such a zone gives rise to a medial moraine.

The upturning of ice here referred to has been observed only at or near the terminus of the ice. It is perhaps due in part to the resistance of frozen morainic or other material beneath and in front of the edge. To this should probably be added the effect of the great rigidity of the ice due to the low external temperature during

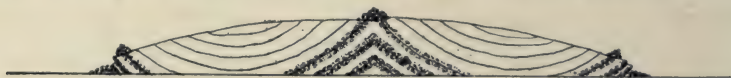


Fig. 216.—Diagram to illustrate one method of formation of medial and lateral moraines. The horizontal line at the base represents sea-level, and the lower part of the glacier is under the sea. The layers of upturning ice bring debris up along the planes of movement, and it accumulates as indicated.

the larger part of the year, while the interior, with its higher temperature, remains more fluent. But even this probably leaves the explanation inadequate.

Wear of drift in transit. Drift carried at the bottom of the ice is much worn, for the materials in transit abrade one another and are abraded by the bed over which they pass. Englacial drift is subject to less wear, because it is commonly more scattered. Superglacial drift is worn little or none while it lies on the surface of the ice; but in so far as superglacial or englacial drift is derived from the basal load, it may show the same evidences of wear as the basal drift itself. Superglacial drift often reveals its history in this way.

DEPOSITION OF THE DRIFT

During the advance of a glacier, deposition may take place both (1) beneath the body of the ice, and (2) beneath its end and edges.

1. Beneath the body of the ice deposition takes place where the topography favors lodgment, or where the ice is overloaded.

The topography favoring deposition is much the same as that favoring erosion, but the two processes are not favored at the same points. Erosion is greatest on the "stoss" side (the side against which the ice advances) of an obstruction, and deposition on the

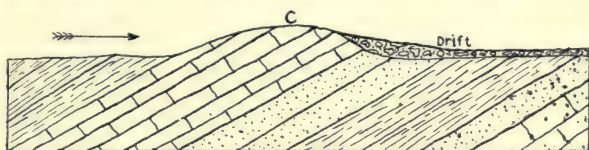


Fig. 217.—Crag and tail. The passage of glacier ice is likely to leave a considerable body of drift in the lee of the boss of rock, C.

lee side (Fig. 217). The ice is likely to be overloaded (1) just beyond a place where conditions have favored the gathering of a heavy load, and (2) where the ice is rapidly thinning. On the



Fig. 218.—Glacier building an embankment. Southeast side of McCormick Bay, North Greenland.

whole, the deposition of material beneath the main body of a glacier is much more than balanced by erosion in the same position.

2. At and near the end of a glacier, deposition goes on faster than elsewhere, chiefly because of the rapid melting, and therefore the thinning and weakening of the ice. If the end of the glacier is stationary in position, drift is being continually brought to it



Fig. 219.— Embankment completed. Near the last.



Fig. 220.— Illecillewæt Glacier; Glacier, British Columbia.

and left there, for it is to be remembered that the ice continues to move though the end is stationary. If the glacier moves forward 500 feet per year, and if its end is melted at the same rate, all the debris in the 500 feet of ice which is melted is deposited, and all except that which has been washed away has been deposited at and beneath the end of the glacier (Figs. 218-219). If the end of the glacier is retreating, the retreat means that the waste at the end



Fig. 221.— The moraines about the lower end of a glaciated mountain valley. Bloody Canyon, Cal. (U. S. Geol. Survey.)

exceeds the forward movement. If the ice advances 500 feet per year and is melted back 600 feet in the same time, all the debris carried by the 600 feet which has been melted has been deposited, and largely in the narrow zone (100 feet) from which the ice has receded. If the end of the glacier is advancing 500 feet per year while it is being melted but 400 feet, all the drift in the 400 feet melted has been deposited, and chiefly at or beneath the immediate margin of the ice. To the marginal and sub-marginal accumulations made in this way, the material carried on the ice is added whenever the ice is melted from beneath it. Deposition beneath the lateral margins of a glacier is much the same as beneath its terminus (Fig. 221).

Types of Moraines

The terminal moraine. The thick accumulation of drift made at the end of a glacier or at the edge of an ice sheet, especially where its end or edge is stationary or nearly so for a considerable time, is the *terminal moraine*. Terminal moraines are of more importance, relatively, in connection with ice-caps than in connection with valley glaciers, for streams are more effective in destroying the moraines of the latter than those of the former.

The ground moraine. When a glacier disappears, all its debris is deposited. All the drift deposited beneath the advancing ice, and all deposited from the base of the ice during its dissolution, constitutes the *ground moraine*. The thickness of the ground moraine is notably unequal. In general, it is thicker toward the terminus of the glacier and thinner toward its source, but considerable portions of a glacier's bed are often left without debris when the ice melts. In general, the ground moraine is thinner than the terminal moraine, and less irregularly disposed. The ground moraine is of relatively slight importance in valley glaciers as compared with ice-caps, since conditions for erosion under the body of a valley glacier are, on the average, better than under an ice-sheet, and those for deposition less favorable.

The lateral moraines. Lateral moraines are the product of valley glaciers. The lateral moraines on such glaciers are let down on the surface beneath when the ice melts; but the lateral moraines in a valley from which the ice has melted are not merely the lateral moraines which were on the glacier at a given time. They are often far more massive than any which ever existed on the ice (Figs. 216, 221, and 222). Furthermore, much of the material of lateral moraines left after the ice is gone is as well worn as that of the ground moraine. The massive lateral moraines left after the ice is gone are made up chiefly of the drift accumulated beneath the lateral margins of the valley glaciers. This accumulation is the result of the lateral motion of the ice from the center to the side of the valley. Such sub-lateral accumulations are akin to terminal moraines. Some of the lateral moraines of ancient valley glaciers, such as those of the Uinta, Wasatch, and Bighorn mountains are

several hundred feet high, or even as much as a thousand. In northern Italy a lateral moraine is said to be about 2,000 feet high.¹

Most of the material which was englacial during its transportation becomes either subglacial or superglacial before deposition, for it reaches the bottom or the top of the ice before being deposited. Only where the ends or edges of a glacier are vertical or nearly so, as in the arctic regions, does deposition take place from the englacial position directly.



Fig. 222.— A lateral moraine left by a former glacier in the Bighorn Mountains of Wyoming. (Photo. by Blackwelder.)

Distinctive nature of glacial deposits. The deposits made by glaciers are distinctive. In the first place, the ice does not assort its material, and boulders, cobbles, pebbles, sand, and clay are confusedly commingled (Fig. 223). In this respect, the deposits of ice differ notably from the deposits of water. Furthermore, many stones of the drift show the peculiar type of wear which glaciers inflict. Though notably worn, they are not rounded like the stones carried by rivers. Many of them have sub-angular forms with planed and beveled faces, the planes being striated and bruised (Fig. 205). Absence of stratification, physical heterogeneity, and the striation of at least a part of the stones are among the most distinctive characteristics of glacial drift. A not less real though

¹ Geikie. *The Great Ice Age*, 3d ed., p. 529.

less obvious characteristic is the constitution of the fine material, for it is, as a rule, the product of rock grinding, not of rock decay.

Glaciated rock surfaces. Another distinctive mark which a glacier leaves behind it is the character of the surface of the rock on which the drift rests. This is generally smoothed by the severe



Fig. 223.— Section of drift showing its heterogeneity.

abrasion to which it has been subjected, and the smoothed surfaces (Figs. 203 and 224) are marked by grooves and striae, similar to those on the stones of the drift (Fig. 205). Other distinctive features of a glaciated area are the rounded bosses of rock (*roches moutonnées*, Fig. 225), the rock basins, the lakes (Fig. 226), ponds, and marshes, and the peculiar topographies resulting from the unequal erosion, and the still more unequal deposition of the drift (Figs. 227 and



Fig. 224.— Ice-worn rock, Bell's Island, Lake Huron. (Bell.)



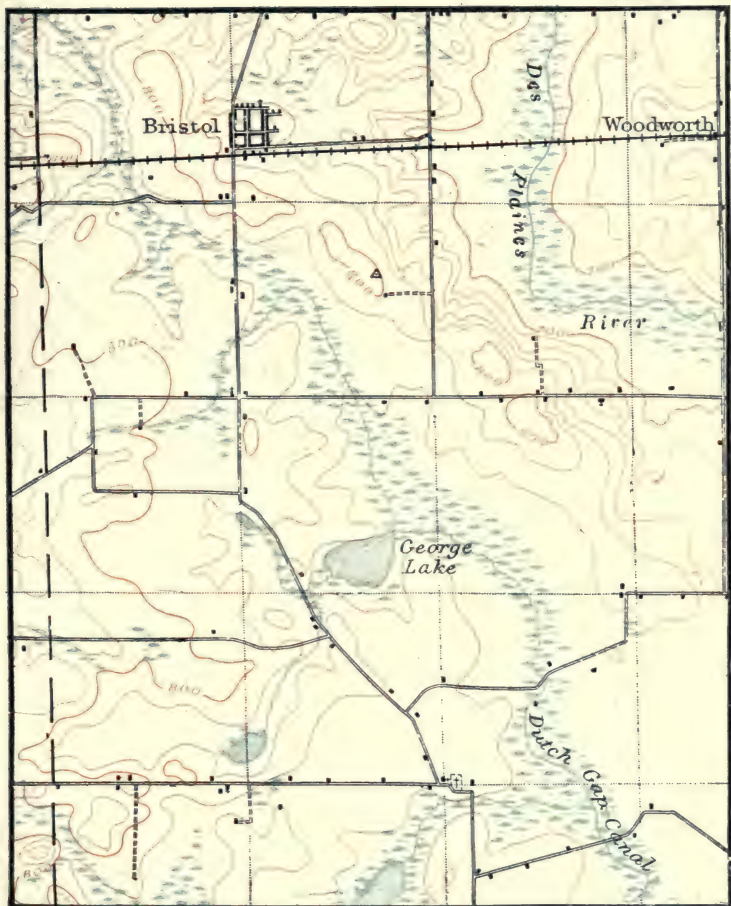
Fig. 225.— Roches moutonnées of gneissic rock on Engineer Mountain, Colo.
Potato Hill in the distance. (Hole, U. S. Geol. Surv.)



Fig. 226.— Island lake near Telluride, Colorado. The lake is about 12,500 feet above sea-level. (Hole.)



Fig. 227.— Sketch of drift (terminal moraine) topography near Hacketts-town, N. J. (N. J. Geol. Surv.)



Characteristic surface of a glaciated plain, showing marshes, ponds, and lakes. Southern Wisconsin. Scale, about 1 mile per inch. (Silver Lake, Wis., Sheet, U. S. Geol. Surv.)

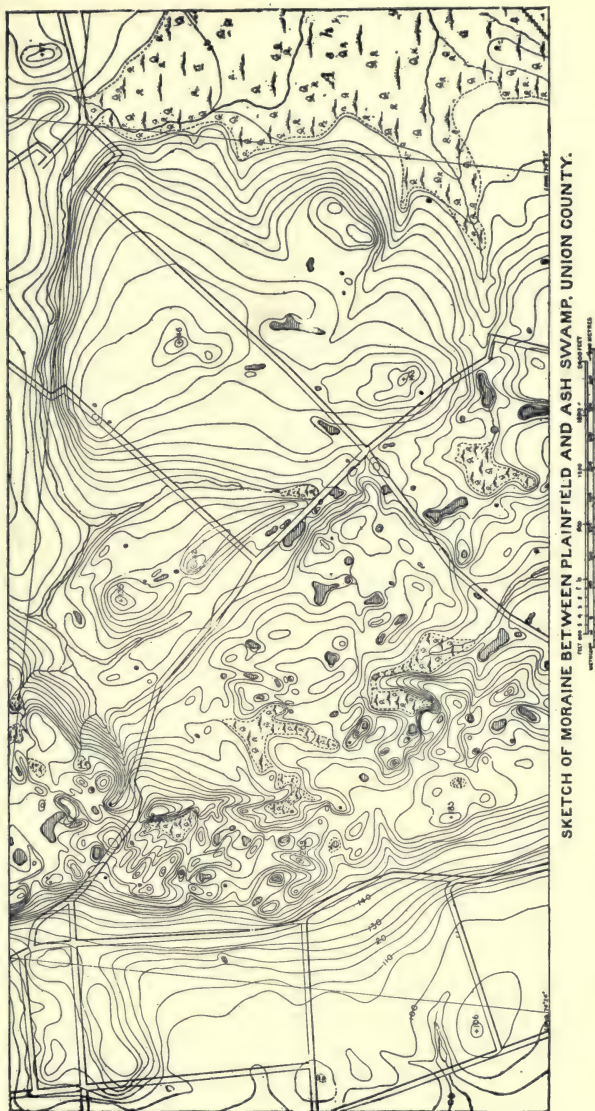


Fig. 228.—Topographic map of a small area of drift in New Jersey. The left central belt of rough topography is *terminal moraine*. The area at the extreme left is drift (gravel and sand) washed out beyond the edge of the ice by streams, making an *outwash plain*.

228, and Pls. XVI and XVII). Surface boulders, often unlike the underlying formations of rock, and sometimes in peculiar and



Fig. 229.— Perched boulder, Argentina. (Robia.)

apparently unstable positions, are still another mark of a glaciated area (Fig. 229).

GLACIO-FLUVIAL WORK

The constant but unequal waste of glaciers has already been referred to. The streams to which the melting of the ice gives rise are unusually laden with gravel, sand, and silt derived from the ice. Since the mud is often light-colored, the streams are some-



Fig. 230.— Diagram to illustrate the profile of a valley train, and its relations to the terminal moraine (*m*) in which it heads.

times described as “milky.” Where the amount of material carried is great, much of it is dropped at a slight distance from the ice, the coarsest being dropped first. Glacial streams are, as a rule, aggrading streams, and therefore develop alluvial plains, called *valley trains* (Fig. 230), or, where they enter lakes, bays, or other streams,

deltas. In its transportation, the river-borne drift is assorted, and after its deposition it is stratified. True glacial deposits in the upper part of a mountain valley are, therefore, often connected with glacio-fluvial deposits farther down the valley. The silt, sand, and gravel of valley trains can often be distinguished from valley deposits of non-glacial origin by the fact that they are more largely of undecayed rock material, especially if deposited recently.



Fig. 231.—Esker of Punkaharju, Finland.

From the ice-sheet, numerous streams flow, spreading their debris in front of the terminal moraine, forming a broad fringing sheet or “apron” (*outwash plain*) along it. Outwash plains have much in common with piedmont alluvial plains. They differ from valley trains chiefly in being shorter, wider, and not confined to a valley. Where streams of considerable size form tunnels under the ice, the tunnels may become more or less filled with water-worn debris, and when the ice melts, the aggraded channels appear as ridges of gravel and sand, known as *eskers* (Fig. 231). It has been thought that eskers represent deposits formed in superglacial channels; but this is probably rarely if ever the case, for the surface

streams usually have high gradients, swift currents, and smooth bottoms, and hence give little opportunity for lodgment. Furthermore, ice-sheets, in connection with which eskers are chiefly de-

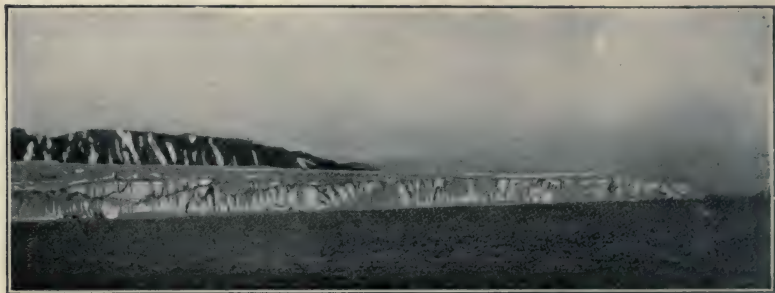


Fig. 232.— The end of a glacier in Spitzbergen. (Rabot.)

veloped, usually have no surface material except at the immediate edge where the ice is thin and its layers upturned.

At the mouths of ice-tunnels or ice-channels, especially where they end against terminal moraines, and in the re-entrant angles

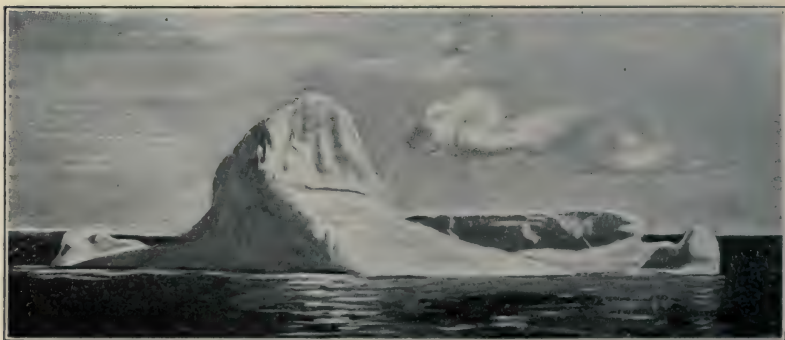


Fig. 233.— An iceberg. (Robin.)

of the edge of the ice, sands and gravels are liable to be bunched in quantity, giving rise, after the adjacent ice has melted, to peculiar hills and hollows of the knob-and-basin type. The hills and short ridges of stratified drift formed in this way are known as *kames*.

Much stratified drift (gravel, sand, and silt) deposited by glacial streams has no distinctive topographic form, and therefore no special name.

ICEBERGS

When glaciers advance into water the depth of which approaches their thickness, their ends are broken off (Fig. 232), and the detached masses float away as icebergs (Fig. 233). Many of the bergs are overturned, or at least tilted, as they set sail. If this does not happen at the outset, it is likely to occur later as the result of the melting, wave-cutting, etc., which shift their centers of gravity. The great majority of bergs do not float far before losing all trace of stony and earthy debris; but the finding of glaciated pebbles in dredgings far south of all glaciers shows that bergs occasionally carry stones far from land.

THE INTIMATE STRUCTURE OF GLACIER ICE

The key to the study of the structure and motion of glacier ice is based on the view that a glacier is a mass of crystalline rock — the purest and simplest type of crystalline rock known. It is made of a single simple mineral, ice, which always has a crystalline structure.

The development of ice from snow. The fundamental conception of a glacier is best developed by tracing the growth of its constituent crystals. When water solidifies from the vapor of the atmosphere, it takes the form of separate crystals (Fig. 234). The flakes are rarely perfect, but they are always crystals. Snow crystals may continue to grow so long as they are in the atmosphere; but if they pass through a dry stratum of air, or a stratum whose temperature is above 32° Fahr., they suffer from melting and evaporation. When they reach the ground, the processes of growth and decadence continue, and the crystals grow or shrink according to circumstances.

A glacier is a colossal aggregation of crystals grown from snow-flakes to granules of greater size and more compact form. The microscopic study of snow reveals the mode of change from flakes to granules. The slender points and angles of new-fallen flakes melt and evaporate more than the central portions. The water

melted from the periphery of a flake may gather about its center, and, if the temperature is right, freeze there. Similarly, evaporation from the periphery is probably followed by condensation about the



Fig. 234.— Photographs of snowflakes, enlarged. (Bentley.)

center. These are first steps toward the pronounced granulation so conspicuous in snow which has lain long on the ground. Measured from day to day, the larger granules beneath the surface of coarse-grained snow are found to be growing. When the temperature of the atmosphere is above the melting-point, the growth is faster than when the air is colder, but there is *an increase in the average size of the granules, and a decrease in their number, under all conditions of temperature.* A part of the increase of the larger granules appears to come from the diminution and destruction of the smaller ones; another part doubtless comes from the moisture of the atmosphere which penetrates the snow and is condensed there, and still another part from the descent of moisture derived from surface melting.

Deep beneath the surface of a large body of snow, the larger part of the growth of the large granules is probably at the expense of the small ones. To understand how this takes place, it should be noted that the free surface of every granule is constantly throwing off particles of water-vapor (i. e., evaporating); that the rate of evaporation increases with the sharpness of the curve of the surface, and that the smaller the particles, the sharper the curve; that the surface of a granule is liable to receive and retain molecules evaporated from other granules, and that, other things being equal, the retention of particles is more common on the surfaces which are least curved. It follows that the larger granules of less curvature will lose less and gain more, on the average, than the smaller granules of greater curvature. The larger granules therefore grow at the expense of the smaller. Furthermore, small granules melt more readily than large ones, and where the temperature is nicely adjusted between melting and freezing, the smaller may lose while the larger gain.

Another factor that affects the growth of the granules is *pressure and tension*. The granules are compressed at the points of contact and put under tension elsewhere, and pressure and tension are, on the average, likely to be relatively greatest for the smallest granules. Tension increases the tendency to evaporation, and the capillary spaces adjacent to the points of contact probably favor condensation. Pressure reduces the melting-point, while tension raises it.

Though the effect of this is slight, it is to be correlated with the much more important fact that *compression produces heat* which may raise the temperature of the ice to the melting-point at some points, while tension may reduce the temperature to or below freezing, at other adjacent points. There is therefore a tendency for the ice *to melt at the points of contact and compression, and for the water so produced to refreeze at adjacent points where the surface is under tension*. This process becomes effective beneath a considerable body of snow, and here the granules gradually lose the spheroidal form assumed in the early stages of granulation, and become irregular polyhedrons, interlocked into a mass of more or less solid ice.

The moisture of the air may be of importance in the process, even far below the surface. Under severe wind pressure, air penetrates porous bodies appreciably, as the "breathing" of soils, "blowing-wells," and "blowing-caves" teach us, for all these things are expressions of the effective penetration and extrusion of the air, under variations of barometric pressure. In the snow-fields, and in the more granular portions of glaciers near their heads, the porosity is doubtless sufficient to make this process effective. The probable effect is two-fold: (1) The condensation within the ice of moisture from the air at some times, and (2) escape of moisture from within the ice at others. These alternating processes are attended by oscillations of temperature which may involve melting and freezing, and these processes produce granular change.

Whether these processes furnish an adequate explanation of the changes or not, all gradations may be observed from snowflakes into granular *névé*, and thence into the granules of glacier ice, ranging in size up to that of walnuts, and even beyond. In coherence, these aggregations vary from the *névé* (coarse-grained snow) stage where the grains are small and spheroidal, to the ice stage where the cohesion is strong through the interlocking growths of the large granules.

Structure and arrangement of the crystals in glacier ice. A crystal of ice is made up of a series of plates arranged at right angles to the principal axis of the crystal. These plates may be likened to a pile of cards, the principal axis being represented by a line vertical to them. If a cube be cut from a large crystal of ice, it will behave

much like a cube cut from the pile of cards. If it is so placed that its plates are horizontal (Fig. 235), and if it is rested on supports at two edges and heavily weighted in the middle, it will sag, the plates sliding slightly over one another. In this case the cube offers considerable resistance to deformation. If the cube is so placed that the plates are on edge, each reaching from support to support (Fig. 236), it will offer very great resistance to deformation. But if the plates are vertical and transverse to the line joining the supports, as in Fig. 237, the middle portion will sag under moderate weighting by the sliding of the plates on one another, and in a comparatively

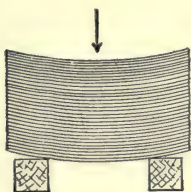


Fig. 235.

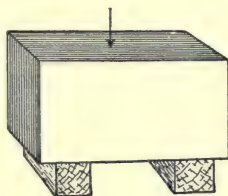


Fig. 236.

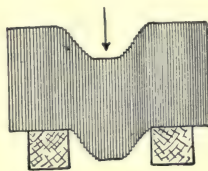


Fig. 237.

Figs. 235, 236, and 237.—Figures to illustrate the method of deformation of ice crystals.

short time the middle portion may be pushed entirely out, dividing the cube.¹ These properties have been made the basis for the hypothesis that glacier motion is primarily the result of the slipping of the plates of the crystal on one another. This hypothesis might have much in its favor if the crystals of ice in the glacier were all oriented so that the plates were parallel with the bed of the glacier; but this is not the case. The crystals, starting from snowflakes, have their axes turned in various directions according to the accidents of their fall; and as the snow develops into ice, the principal axes of the granules continue to lie in all directions.

There does appear to be a tendency, however, for the crystals of ice to approach parallelism in the basal, terminal part of a glacier. From such observations on this point as are available, it is probable that the parallel orientation is due (1) partly to the vertical pressure

¹ McConnel and Mügge. On the Plasticity of Glaciers and Other Ice. *Proc. Roy. Soc.*, Vol. XLIV, 1888, pp. 331-67 (with D. A. Kidd); Vol. XLVIII, 1890, pp. 259, 260; Vol. XLIX, 1891, pp. 323-43.

of ice, and (2) partly to the shearing and foliation of the ice, or to the causes which produce these structures. In this position, then, the slipping of crystal plates on one another may be a factor in glacial motion.

The Probable Fundamental Element in Glacier Motion

Melting and freezing. There seems to be no escape from the conclusion that the primal cause of glacier motion is one which may operate even under the relatively low temperatures, the relatively dry conditions, and the relatively granular textures which affect the heads of glaciers. These considerations lead to the view that movement there takes place by the minute individual movements of the grains upon one another. While they are in the spheroidal form, as in the *névé*, this would not seem to be difficult. They may rotate and slide over each other as the weight of the *névé* increases. After they become interlocked by further growth, rotation and sliding must be more difficult. The amount of motion required of an individual granule is surprisingly small. In order to account for a movement of three feet per day in a glacier six miles long, the mean motion of the average granule relative to its neighbor would be roundly, $\frac{1}{10000}$ of its own diameter per day; in other words, it *should change its relations to its neighbors* to the extent of its diameter once in about thirty years. A change of such slowness under the conditions of granular alteration can scarcely be thought incredible, or even improbable, in spite of the interlocking which the granules may develop. It is conceivable that there may be motion between the granules comparable to that between shot in great quantities in similar positions; but the movement is supposed to be effected chiefly by the temporary passage of minute portions of the granules into the fluid form at the points of greatest compression, the transfer of the water thus produced to adjoining points, and its resolidification. The points of greatest compression are obviously those whose yielding most promotes motion, and the successive yielding of points which come in succession to oppose motion most (and thus to receive the greatest stresses), permits continuous motion. It is only necessary to assume that the gravity of the accumulated mass is sufficient to produce a little temporary liquefaction at the points

of greatest stress, the result being accomplished not so much by the lowering of the melting-point as by the development of heat by pressure.

This conception of glacial movement involves the *momentary liquefaction of minute portions of the ice*, while the mass as a whole remains rigid, as its crystalline nature requires. Instead of assigning a slow viscous fluidity like that of asphalt to the *whole* mass, which seems inconsistent with its crystalline character, it assigns a free fluidity, momentarily, to a succession of particles that form only a minute fraction of the whole at any instant.

This conception is consistent with the retention of the granular condition of the ice, with the heterogeneous (in the main) orientation of the crystals, with the rigidity and brittleness of the ice, and with its strictly crystalline character, a character which a viscous liquid does not possess, however much its high viscosity may make it resemble a rigid body.

Accumulated motion in the terminal part of a glacier. However slight the relative motion of one granule on its neighbor, the granules in any part of a glacier partake in the accumulated motion of all parts nearer the source, and hence all except those at the head are *thrust forward*. Herein appears to lie the distinctive nature of glacial movement. Each part of a stream of water feels (1) the hydrostatic pressure of neighboring parts (theoretically equal in *all* directions), and (2) the momentum of motion, but *not the thrust of the water up stream*. This is probably one of the fundamental differences between water flow and glacier motion.

Lava streams are good examples of viscous fluids flowing in masses comparable to those of glaciers, on similar slopes, and, in the later stages of motion, at similar rates; but their special modes of flow and their effects on the sides and bottoms of their paths are radically different from those of glaciers. Forceful abrasion, and particularly the rigid holding of imbedded stones which score and groove the rock beneath, is unknown in lava streams, and is scarcely conceivable. There is, so far as we know, no experimental or natural evidence that any viscous fluid, in the ordinary sense of that term, detaches and picks up fragments and holds them firmly as graving tools in its base so as to cut deep, long, straight grooves

in the hard bottom over which it flows. It would seem that competency on the part of a viscous body to do this peculiar class of work so distinctive of glaciers, should be demonstrated before the viscous theory of glacial movement is accepted as even a good working hypothesis. In contrast with viscous movement, it is conceived that a glacier is thrust forward rigidly by internal elonga-



Fig. 238.—Shearing plane in glacier well defined; a Spitzbergen glacier. (Hamberg.)

tion, and that it is sheared forcibly over its sides and bottoms, leaving its distinctive marks upon them.

Auxiliary Elements

Shearing. In the lower part of a glacier, where the thrusts are greatest, normally, where the granules are fewest and their interlocking most intimate, shearing takes place within the ice. This is illustrated by Figs. 238 and 239. The shearing results in the foliation of the ice, and in the dragging of debris along the planes of shear. Thus the ice becomes loaded in a special englacial, or baso-englacial fashion, as previously mentioned and illustrated.

Within the zone of shearing, the gliding planes of the crystals may come into effective function. It is thought that the combined effect of the vertical pressure, the forward thrust, and the basal drag of the ice, may be to increase the number of granules whose gliding planes are parallel to the glacier's bottom. At any rate, such an arrangement in the basal portion of the Greenland glaciers at their borders is said to exist. It is conceived that where strong thrusts are brought to bear upon such a mass of granules, those



Fig. 239.— Portion of the east face of Bowdoin Glacier, North Greenland, showing oblique upward thrust, with shear.

whose gliding planes are parallel to the direction of thrust are strained with sufficient intensity to cause the plates to slide over each other, while those which are not parallel to the direction of thrust are either rotated into parallelism — when they also yield — or are pressed aside out of the plane of shear. As previously noted, shearing is observed to occur chiefly where the ice below the plane of shearing is protected more or less from the force of the thrust, as in the lee of a hill or mass of *débris*. It perhaps also occurs at the top of the basal zone of ice so loaded with *débris* that it is incapable of ready movement.

It is probable, also, that sharp differential strains and shearing are developed at the level where the surface water of the warm season, descending into the ice, reaches the zone of freezing; for the expanding of the freezing water at the upper limit of the cold zone may cause the layer expanded by it to shear over that below. As the level of freezing descends with the advance of the warm season, the zone of shearing sinks. This is a phase of shearing developed in a special horizon relatively near the surface. It may be noted that expansion at the zone where descending water freezes, not only leads to shear, but to the development of surface cracks, for the surface is stretched as the zone below expands. In the course of years, the cracks developed in this way may become wide crevasses, limited below by the depth of the zone of freezing in summer.

High temperature and water. In the zone of waste, the higher temperature and the greater abundance of water lend their aid to the fundamental agencies of movement; and there is need for these aids to promote a proportionate movement, for here the granules are more intimately interlocked, and the ice more compact and inherently more solid and rigid. The average temperature is near the melting-point (p. 247), and during the warm season the ice is bathed in water all the time, so that the necessary changes in the crystals are facilitated. Under these conditions, movement takes place more readily than in the more open granular ice of lower temperature and drier state.

Application. The co-operation of the auxiliary agencies of motion with the fundamental ones appears to explain the peculiarities of glacial movement. In regions of intense cold, where a dry state and low temperature prevail, as in the heart of Greenland, the snow-ice mass may attain an extraordinary thickness. Here the burden of movement seems to be thrown almost wholly upon compression, with the slight aid of molecular changes due to internal evaporation and allied inefficient processes. Since the temperature in the upper part of the ice is very adverse (p. 245), the compression must be great before it becomes effective in melting the ice, and hence the great thickness of the snow before motion is considerable. Similar conditions more or less affect the heads of Alpine glaciers, though here the high gradients favor motion with

lesser thicknesses of ice. In the lower reaches of Alpine glaciers, where the temperatures are near the melting-point, and where the ice is bathed in water much of the time, movement may take place in the ice which is thin and compact.

If the views here presented are correct, there is also, at all points below the source, the cooperation of rigid thrust from behind, with the tendency of the mass to move on its own account. The latter is controlled by gravity, and conforms *in its results* to laws of liquid flow. The former is a derived factor, and is a mechanical thrust. This thrust is different from the pressure of the upper part of a liquid stream on the lower part, because it is transmitted through a body whose rigidity is effective, while the latter is transmitted on the hydrostatic principle of equal pressure in all directions. Thrust would be most effective toward the end or edge of a glacier.

Corroborative Phenomena

The conception of the glacier and its movement here presented explains some of the anomalies that otherwise seem paradoxical. If the ice is always a rigid body which yields only as its interlocking granules change their form by loss and gain, a rigid hold on the imbedded rock at some times, and a yielding hold at others, is intelligible. Stones in the base of a glacier may be held with great rigidity when the ice is dry, scoring the bottom with much force, while they may be rotated with relative ease when the ice is wet. In short, the relation of the ice to the boulders in its bottom varies radically according to its dryness and temperature. *A dry glacier is a rigid glacier. A dry glacier is necessarily cold, and a cold glacier is necessarily dry.*

It is difficult to explain the furrows and grooves cut by glaciers in firm rock if the ice is so yielding as to flow under its own weight on a surface which is almost flat. If the mass is really viscous, its hold on its imbedded debris should also be viscous, and a boulder in the bottom should be rotated in the yielding mass when its lower point catches on the rock beneath, instead of being held firmly while a groove is cut. This is especially to the point since viscous fluids flow by a partially rotary movement.

On the view here presented, a glacier should be more rigid in

winter than in summer. The total thickness of a glacier should experience this rigidity of winter at its ends and edges, where the ice is thin enough to permit the low temperature to affect its bottom. The motion in these parts during the winter is, therefore, very small.

In this view, also, may be found an explanation of the movement of glaciers for considerable distances up-slope, even when the *surface* of the ice, as well as its bed, is inclined backwards. So far does this go, that superglacial streams sometimes run for some distance *backwards*, i. e., toward the heads of the glaciers, while in other places surface waters are collected into ponds and lakelets. Such a slope of the surface of ice is not difficult to understand if the movement is due to thrust from behind, or if it is occasioned by internal crystalline changes acting on a rigid body; but it must be regarded as very remarkable if the movement of the ice is that of a fluid body, no matter how viscous, for the length of the acclivity is sometimes several times the thickness of the ice. Crevassing and other evidences of brittleness and rigidity find a ready elucidation under the view that the ice is really a solid body at all times, and that its apparent fluency is due to the momentary fluidity of small portions of its mass assumed in succession as compression demands.

In addition to the considerations already adduced, it may be urged that a glacier does not flow as a stiff liquid because its granules are not habitually drawn out into elongated forms, as are cavities in lavas, and plastic lumps in viscous bodies. Flowage lines comparable to those in lavas are unknown in glaciers.

All this is strictly consistent with our primary thesis, that a glacier is crystalline rock of the purest and simplest type, and that it never has other than the crystalline state. This strictly crystalline character is incompatible with viscous liquidity.

Other Views of Glacier Motion

While these views of glacial motion seem to us to best accord with the known facts, they are not to be regarded as established in scientific opinion, or as the views most commonly held. The mode of glacial motion has long been a mooted question, and is still so

regarded. The main alternative interpretations that have been entertained are the following:

(1) In the early days of glacial studies De Saussure thought that glaciers slid bodily on their beds.

(2) Charpentier and Agassiz referred the movement to the expansion of descending water freezing within the glacier.

(3) Rendu and Forbes, followed by many modern writers, believed ice to be viscous, and that in sufficiently large masses it flows under the influence of its own weight, like pitch or asphalt.

(4) Others, realizing the fundamental difference between crystalline ice and a true viscous body, have fallen back on a vague notion of plasticity, which scarcely amounts to a definite hypothesis at all.

(5) Tyndall urged that the movement was accomplished by minute repeated fracturing and regelation, appealing to the fact that broken pieces of ice slightly pressed together at melting temperatures freeze together, but neglecting the fact that this would destroy the integrity of the crystals.

(6) Moseley assigned the movement to a bodily expansion and contraction of the glacier, analogous to the creeping of a mass of lead on a roof.

(7) James Thompson demonstrated that pressure lowers the melting-point, and while this effect is so small as probably to be ineffectual, it is correlated with the very important fact that compression may cause melting, which is not the case in most other rocks. He recognized that under pressure partial liquefaction took place, that the water so liberated might be re-frozen as it escaped from pressure, and appears to have regarded this as a vital factor.

(8) Croll held that the movement was due to a consecutive series of molecular changes somewhat like the chain of chemical combinations in electrolysis.

(9) Hugi, Eli de Beaumont, Bertin, Forel, and others thought that the growth of the granules was the leading factor in the ice movement.

(10) McConnel and Mügge have made the gliding planes of the ice crystals serve an important function in glacial movement.

It will be seen that the principle of partial liquefaction for which Thompson laid the basis, the crystallization of descending water, urged by Charpentier and Agassiz, and the granular growth on which Hugi, Beaumont, Forel, and others founded their hypotheses, are incorporated in the view already presented. Probably the agencies on which some of the other views are based may also be participants in producing glacial motion, sometimes as incidental factors, and sometimes perhaps as important ones, for under different conditions, different agencies may play rôles of varying importance. For example, in going over the brinks of precipices of sufficient height, glaciers break into fragments which are cemented below, and the "reconstructed" glacier moves on as before. Here fracture and regelation are evident, though they are hardly causes of motion. The movement of the gliding planes of the ice crystals over each other, which has been looked upon as a special kind of viscid movement, probably plays a part in shearing. But neither of these is probably a large factor in ordinary glacial movement, and it seems highly improbable that any of them are essential factors in the movements in the snowfields where glacial motion begins.

Map work. The effects of glaciation are well shown on many of the topographic maps of the U. S. Geological Survey. Lists of such maps are found on pages 230 and 289 of the junior author's *Physiography*, Advanced Course. Plates XCV to CXXIX, found in Professional Paper 60, U. S. Geological Survey, present a number of maps illustrating this topic.

CHAPTER VII

THE WORK OF THE OCEAN

A few facts concerning the depth of the ocean and the distribution of its water have been given on a preceding page (p. 6), and some reference to the origin of the ocean basins and the ocean will be made later. We are concerned here chiefly with the geologic processes now going on in the sea; but a few facts concerning the sea-water and its life, and the topography of the ocean's bed,¹ may well precede the study of the processes now in operation.

Mineral matter in solution. Every 1,000 parts of sea-water contain about 34.40 parts by weight of mineral matter in solution. The principal solids are shown in the following table:²

Chloride of sodium	77.758
Chloride of magnesium.....	10.878
Sulphate of magnesium.....	4.737
Sulphate of calcium.....	3.600
Sulphate of potassium.....	2.465
Bromide of magnesium.	0.217
Carbonate of calcium.....	0.345

The presence of many other mineral substances in sea-water has been proved, and oxygen, nitrogen, and carbon dioxide are present in quantity. The amount of carbonic acid is estimated to be 18 times as great as in the atmosphere.

The amount of sea-water is estimated by Murray at 323,722,150 cubic miles,³ or about 15 times the volume of the land above sea-level. The volume and composition of the sea-water being known,

¹ Much information on these and other points is to be found in the following books: Wild's *Thalassa*; Thompson's *Depths of the Sea*; Barker's *Deep Sea Soundings*, and Maury's *Physical Geography*. Agassiz's *The Three Cruises of the Blake*, and the *Challenger Reports* give much more detailed information for certain regions.

² Dittmar, *Challenger Reports*, Physics and Chemistry, Vol. I, p. 204.

³ Murray, *Scot. Geog. Mag.*, Vol. IV, p. 39.

the amount of mineral matter which it contains may be readily calculated. Assuming the average specific gravity of the mineral matter to be 2.5, the 3.5% (nearly) by weight becomes about 1.4% by volume, and 1.4% of 323,722,150 cubic miles is 4,532,110 cubic miles. This represents the aggregate volume of mineral matter in the sea if it were precipitated and compacted so as to have an average specific gravity of 2.5. This amount of mineral matter would cover the ocean bottom to a depth of about 175 feet. Its amount is equal to about 20% of that of all lands above sea-level.

A large part of the mineral matter of the sea has come from the land, having been extracted from it by ground-water, and carried by rivers to the sea. But the mineral matter of the sea gives no more than a hint of the importance of the solvent work of water in the general processes of rock decay, for most of the mineral matter carried from the land to the sea in solution is taken from the sea-water about as rapidly as it is supplied. Calcium carbonate, for example, is about twenty times as abundant as sodium chloride in river-water, but it is only $\frac{1}{2\frac{1}{2}5}$ as abundant in sea-water. This is because the calcium carbonate is used by animals and plants to make shells, skeletons, etc., while the salt remains in solution.

Knowing, approximately, the amount of water discharged by rivers into the sea each year (about 6,500 cubic miles¹), and knowing the amount of salt it carries, it is calculated that it would take about 370,000,000 years for the salt of the sea to have been contributed by the rivers, at the present rate. It is to be understood, however, that this figure cannot be taken as the age of the ocean, for (1) the salt is not all brought in by rivers, (2) it is not probable that the rivers have always contributed salt at the present rate, and (3) much salt once in the sea has been precipitated. Nevertheless the above figure gives some suggestion as to the order of magnitude of the figure which represents the age of the ocean. All of the calcium carbonate in the sea would be given to it by rivers in about 62,000 years at their present rate of contribution.

Topography of the ocean bed. The ocean basins are pronouncedly convex upward. It is only when we remember that a level surface (on the earth) is one which has the mean curvature

¹ Murray, Scot. Geog. Mag., Vol. III, p. 70.

of the earth, and that the deeper parts of the ocean basin are considerably below the mean sphere level, that the name basin seems appropriate.

The bed of the ocean, like the face of the land, is affected by elevations and depressions, and its deepest parts are about as far below its surface as the highest mountains are above it. If the water were drawn off, so that the bottoms of the ocean basins could be seen, three great features would appear: (1) Extensive tracts of low land, now covered by deep water; (2) other great, but less extensive tracts of higher land, now covered by shallow water; and (3) ridges and peaks of mountainous heights. These three principal divisions may be compared to the plains, plateaus, and mountains of the land, though mountain systems would be less numerous than on land. Furthermore, there would be found great depressions comparable to the great basins of the land.

Apart from these general features, there is little in common between the topography of the sea bottom and that of the land. If the water were drawn off from the ocean's bed so that it could be seen as the land is, its most impressive feature would be its monotony. The familiar hills and valleys which, in all their multitudinous forms, give the land its most familiar features, are essentially absent. A large part of the ocean bottom is so nearly flat that the eye would not detect its departure from planeness, if the water were absent.

The reason for this profound difference is readily found. The dominant processes which shape the details of the surface of the land are degradational, and though the final result of degradation is flatness (base-level), the immediate result is roughness. In the sea, the dominant processes are aggradational, and tend to monotonous planeness.

Distribution of marine life. Marine life has been of such importance in the history of the earth that the elementary facts concerning its distribution and the principles which control it are here recalled. The distribution of marine life is influenced by many factors, chief among which are *temperature* and *depth of water*. Life is more abundant in the warmer parts of the ocean than in the colder, the species inhabiting cold waters are different from those in

warm, and few species range through great variations. Many forms of life are restricted to shallow water; many others, especially those which live near the surface, swim about freely without reference to the depth of the water beneath them; while a few are restricted to great depths. Some species are also influenced by (1) the *salinity of the water*, which varies notably along coasts where the fresh waters from the land are discharged; (2) the *character of the sediment* at the bottom, some species preferring mud, others sand, etc.; (3) the *movement of the water*, some species preferring still water and others rough; (4) the *abundance and nature of the food-supply*; and (5) the *presence or absence of rival and hostile species*.

Subject to the exceptions determined by temperature, etc., plant life abounds in shallow water out to depths of 100 fathoms or so, and is found in abundance at the surface where the depth is much greater. Animal life abounds in shallow water, both at the bottom and above it, out to depths of 200 or 300 fathoms, and occurs in great profusion in the surface-waters of temperate and tropical regions without regard to the depth. The great body of the ocean-water lying below a depth of some few hundred fathoms is nearly tenantless, though life reappears sparingly at the bottom, even where the depth is great.

PROCESSES IN OPERATION IN THE SEA

Diastrophism, vulcanism, and gradation are operative on the bottom of the sea as on the land.

Diastrophism. So far as the lithosphere is concerned, the sea-level is the *critical level*. At and above it, many processes are going on which are not operative below, and below sea-level, some which do not take place above. Warpings of the surface which do not involve the submergence of areas which were land, or the emergence of areas which were under water, are relatively unimportant compared with those which effect such changes. The rise of the bottom of the sea from a depth of 400 fathoms to a depth of 200 fathoms would not have important results, so far as the area itself is concerned, while an equal rise of the bottom beneath 100 fathoms of water, or an equal subsidence of land 500 feet high,

would be attended by more striking consequences. It follows that the changes effected by diastrophism are much more obvious in shallow water than in deep. Emergence or submergence shifts the zone of contact of ocean and land, and so the areas of aggradation

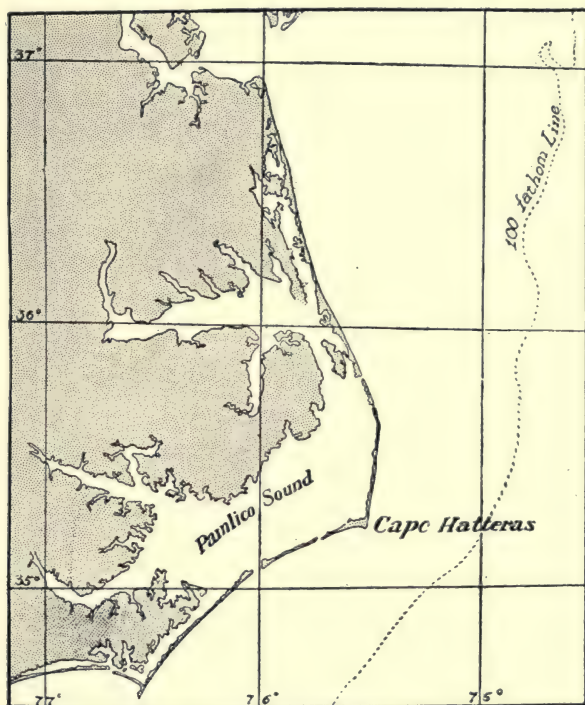


Fig. 240.— Map showing the early stages in the simplification of a shoreline, and showing that at this stage the irregularities are increased.

and degradation, and changes the region concerned from one appropriate for sea life to one appropriate for land life, or *vice versa*.

Over the continental shelves the water is shallow and the bottom relatively smooth. If the sea-level is drawn down, or if the continental shelf is elevated evenly, the new shore-line on the smooth surface of the former submerged shelf will be relatively regular, even though the coast was notably irregular before the change. This is illustrated by Fig. 240. Subsidence of a coast-line (or rise

of the sea-level) tends to the opposite results, for in this case the sea advances on a surface which has relief, and the water enters every depression brought to its level. Thus the numerous bays at the lower ends of the streams along the Atlantic coast from Long Island Sound to Carolina are the results of recent sinking. From the present configuration of coast-lines it has been inferred that the

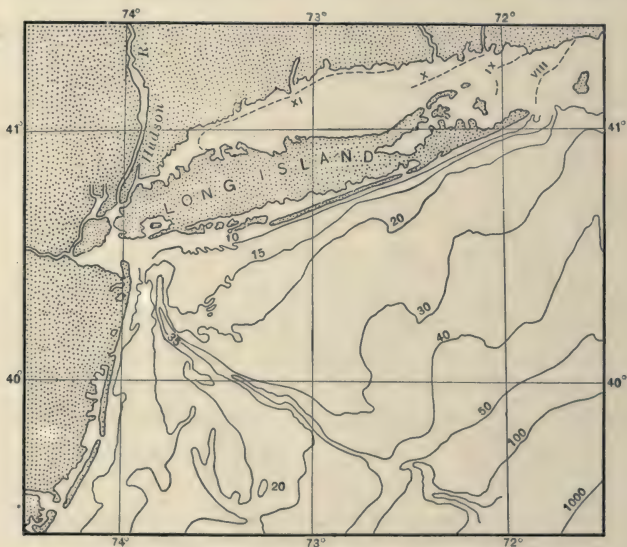


Fig. 241.—The submerged valley which has been interpreted as the continuation of the Hudson Valley. The position of the valley is indicated by contours. (Data from C. and G. Survey.)

present is, on the whole, an era of continental depression.¹ River valleys, the lower ends of which are embayed, are sometimes found to be continuous with submerged valleys beyond the coast-line (Fig. 241). Submerged river valleys show that the surface in which they lie was once land.

The effects of diastrophism in the ocean and about its borders, may (1) make the water of any ocean, or of any part of it, shallower or deeper; (2) cause the emergence or submergence of land; (3) make coast-lines regular or irregular; (4) shift the habitat of many

¹ J. Geikie, *Earth Sculpture*, p. 329.

forms of life, and, through these changes, (5) influence the processes of gradation, especially at the contact of sea and land.

Vulcanism affects the sea-bottom much as it affects the land. At the volcanic centers, where the great body of extruded matter accumulates, mounds and mountains are built up, and most of the mountain peaks of the sea-bottom had a volcanic origin. Where volcanic cones are built up near the surface of the sea, they often furnish a home for shallow-water life, such as polyps. Wherever they are built up so as to be within the reach of waves, gradational processes are stimulated.

The number of active volcanoes on islands is about 200, but the number of active vents beneath the sea is unknown. A few submarine eruptions have been observed, but those observed are probably but a small percentage of those which have taken place in historic time, for slight eruptions in deep water might not be seen at the surface, even if observers were near.

Oceanic volcanoes affect both the temperature and the composition of the sea-water. Both the increase of temperature and the solution of volcanic gases increase the solvent power of water, and both the change in temperature and composition affect the life of the adjacent waters. The decay of organisms destroyed during eruptions generates gases, and these gases may lead to further chemical changes. Volcanoes in the sea have furnished much of the material now found on the bottom of the ocean. Some of this material is very fine, like volcanic dust, and some of it is much coarser. Both the very fine material and the pumice may be distributed far from the volcanoes which emit them. As a matter of fact, they are found nearly everywhere on the bottom of the deep sea, though not in uniform abundance. From these considerations it is apparent that the effects of oceanic volcanoes on the sea-water are considerable, when long periods of time are considered.

Gradation. The gradational processes of the land and the sea are in striking contrast. On the land, degradation predominates, and aggradation is subordinate; in the sea, aggradation predominates and degradation is subordinate. On the land, degradation is greatest, on the whole, where the land is highest, while aggradation is of consequence only where the land is low, or where steep

slopes give place to gentle ones. In the sea, degradation is virtually confined to shallow water, or to what might be called the highlands of the sea, while aggradation is nearly universal, though most considerable in shallow water, or where shallow water gives place to deep. Both the degradational and aggradational work of the sea are greatest near its shores. Though the gradational work of the land and sea are in strong contrast, they tend to a common end — the leveling of the surface of the lithosphere.

The gradational processes of the sea-bottom are effected (1) by mechanical, (2) chemical, and (3) organic agencies. The *mechanical* work of gradation in the sea is effected chiefly by the movements of the water. These movements may be degradational where the water is shallow enough for the motion to affect the bottom, but elsewhere they are aggradational. The gradational work effected by *chemical* means is likewise partly degradational and partly aggradational. In lagoons and other small inclosures, the water may become super-saturated with some mineral substance; precipitation then takes place, the precipitate accumulating as sediment on the bottom. On the other hand, solution results in degradation. *Organic* agencies are, on the whole, aggradational. Accumulations of coral, coral debris, shells, etc., help to build up the sea-bottom, and most rapidly in shallow water where the forms of life which secrete calcium carbonate are most abundant. In the aggradation effected directly by organic agencies, the sea is passive. Its only part is to support the life which gives rise to the solid matter, and incidentally to float a part of it in its currents.

Movements of the sea-water. The movements of the sea-water fall into several categories. There is (1) a general circulation of sea-water, determined chiefly by (a) differences in density in the sea-water, (b) differences of level, and (c) movements of the atmosphere; (2) periodic tidal movements; and (3) aperiodic movements due to occasional causes, such as earthquakes, volcanic explosions, landslides, etc.

For present purposes, all movements of the sea-water may be grouped into two main classes — (1) waves, with the undertow and the littoral currents they generate, and (2) ocean-currents.

Waves

Wave-motion.¹ The most common waves are those generated by winds. During the passage of a wave, each particle affected by it rises and falls and moves forward and backward, describing an orbit in a vertical plane. If the passing wave is a swell, the orbit of the particle is closed and is either a circle or an ellipse; but in the case of a wind-wave the orbit is not closed, for in such a wave the water, as well as the undulation, moves forward. On the crest of the wind-wave each particle of water moves forward, and in the trough it moves less rapidly backward, and the excess of the forward movement over the backward gives the water a slight residual advance. This advance is the initiatory element of current. As a result of this advance, the upper layer of water is carried forward with reference to the layer below, in the direction toward which the wind blows. The waves of any considerable or long-continued wind, therefore, generate a current tending in the same direction as the wind.

The wave motion is propagated indefinitely downward, but the amount of motion diminishes rapidly with increasing depth (Fig. 242.) Engineering operations have shown that submarine structures are little disturbed at depths of five meters in the Mediterranean, and eight meters in the Atlantic. On the other hand, debris as coarse as gravel, which is transported by rolling on the bottom, is not infrequently carried out to depths of 50 feet, and sometimes even to 150 feet. Fine sediment, like silt, is disturbed at still

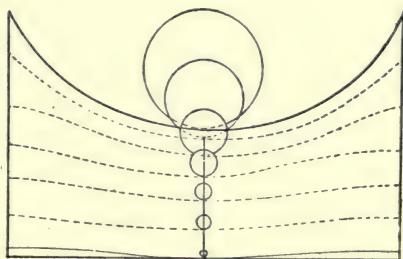


Fig. 242.—Diagram illustrating the decreasing size of the orbits of water particles in a wave, with increasing depth. (Fenneman.)

¹ In the following pages concerning the waves and their work, Gilbert's discussion of shore features, in the Fifth Annual Report of the U. S. Geol. Survey, pp. 80-100, is freely drawn on. Another incisive discussion of certain shore phenomena is that of Fenneman, *Jour. of Geol.*, Vol. X, pp. 1-32.

greater depths, for ripple-marks, which indicate agitation of the water, are said to have been found at depths of 100 fathoms.

When a wave approaches a shelving shore, its habit is changed. The velocity of the undulation is diminished, while the velocity of the advancing particle of water in the crest is increased; the wave-length, measured from trough to trough, is diminished, and the wave-height is increased; the crest becomes acute, with the

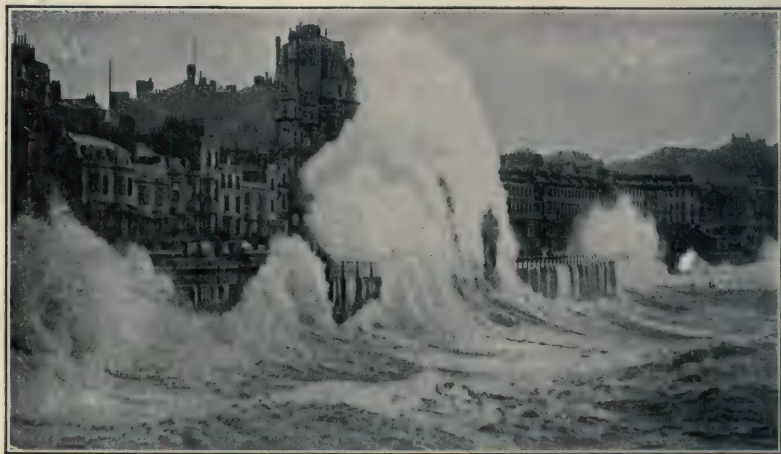


Fig. 243.— Shore wave breaking on east wall of Hastings. (From Wheeler's *The Sea Coast*; by permission of Longmans, Green and Company.)

front steeper than the back, and these changes culminate in the breaking of the crest, when the undulation proper ceases. Waves of a given height break in about the same depth of water, and the line along which incoming waves break is the line of *breakers*. The line of breakers is in deepest water and farthest from shore when the waves are strong. The return of the water thrown forward in the crests of waves is accomplished by a current along the bottom called the *undertow*. The undertow is sensibly normal to the coast when uninfluenced by oblique waves, and is efficient in removing the products of erosion.

When waves advance on the shore obliquely, a shore-current is

developed as illustrated by Fig. 244, where ab represents the direction of the incoming wave, bc the direction of the shore (or, *littoral*) current, and bd the direction of the undertow. Where they strike the borders of land, the wind-waves, therefore, generate two other movements, the undertow and the littoral current. Any particle of water near shore may be affected by any two or by all three of these movements at the same moment. The effect of littoral current and undertow is to give a particle of water on which both are working a direction between the two, as be . The effect of other combinations can be readily inferred. These various combinations are of consequence in the transportation of debris.

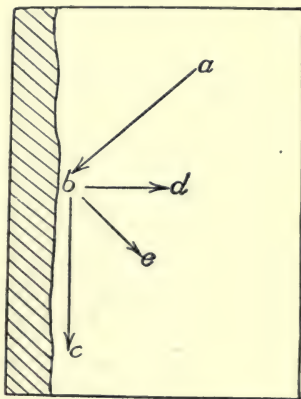


Fig. 244.— Diagram showing relative directions of wave, undertow, and shore-current.

Work of the Waves

The general effects on shores of the waves and the other movements to which they give rise are (1) the wear of the shores; (2) the transportation of the products of wear; and (3) the deposition of the transported materials.

Erosion. In the dash of the waves against the shore, the wear is effected chiefly by the impact of the water and of the debris which the water carries, but lesser results are accomplished in other ways.

When the land at the margin of the water consists of unconsolidated material, or of fragmental material but slightly cemented, the dash of the water is sufficient to displace or erode it. If weak rock is associated with resistant rock within the zone of wave-work, the removal of the former may lead to the disruption and fall of the latter, especially when weak rock is washed out from beneath strong. The impact of the water is competent also to break up and remove rock which was once resistant, but which has been weakened by weathering. Rock affected by joints is likewise attacked with

success, for the blocks bounded by joints may be loosened and literally quarried out. Waves of clear water, even when their force is many tons to the square foot, have little effect on rock which is thoroughly solid.

The impact of the waves is generally reinforced by the detritus they carry. The sand, the pebbles, and such stones as the waves



Fig. 245.— Angular blocks of rock which have fallen from the cliff above, as a result of undercutting by the waves; Grand Island, Lake Champlain. The rock is Black River limestone. Although from the shore of a lake instead of the sea, the principles illustrated are the same. (Perry.)

can move are used as weapons of attack, both against the shore and against one another. Masses of rock too large for the waves to move (Fig. 245) are worn by the detritus driven back and forth over them, and in time reduced to movable dimensions. They then become the tools of the waves, and, in use, are reduced to smaller and smaller size. Thus boulders are reduced to cobbles, cobbles to pebbles, pebbles to sand, and sand to silt. The silt, held in suspension in agitated water, is carried out beyond the

range of breakers, and settles in water so deep as not to be effectively agitated to its bottom. Thus one generation of bowlders after another is worn out, and the comminuted products are carried out from the immediate shore and deposited in deeper water.

The effectiveness of waves depends on their strength and on the concentration of their blows.¹ The strength of waves is dependent on the strength of the winds (or other generating cause) and the depth and expanse of the water, and the concentration of their blows is determined by the slope against which they break. On exposed ocean-coasts the fetch of the waves is always great. The winds are variable. For a given coast they have an average strength, but the effectiveness of wave-erosion is determined less by the average strength of waves than by the strength of the storm-waves. The average force of waves on the Atlantic coast of Britain has been found to be 611 lbs. per square foot in summer, and 2,086 lbs. in winter, but winter breakers which exert a pressure of three tons per square foot are not infrequent. Exceptional storm-waves are known to have moved blocks of rock exceeding 100 tons in weight. Waves are most efficient on bold coasts bordered by broad expanses of deep water, for here the force of the wave is almost wholly expended near the water line; where shallow water borders the land, the force of the waves is expended over a greater area.

The less familiar phases of wave-work are accomplished by hydraulic pressure, compressed air, shore ice, etc. When the water of a wave is driven into an open joint or a cave, the hydraulic pressure may be so great as to break the rock if it is weak. When water is driven with force into a cave, the compression of the air may be great if the wave is high enough to close the entrance. When the water runs out of a cave, the air within may be greatly rarefied, while that above exerts its normal pressure. In either case the roof of the cave, if it is weak, may be broken. At certain seasons of the year, especially during the spring, waves make destructive use of the ice which is then breaking up, but it is only in high latitudes that sea-ice is of importance in this way. In

¹ Willis, Jour. of Geol., Vol. I, p. 481.

general, the effect of its presence in keeping down waves over-balances its effect as an agent of erosion.

The direct effect of wave-erosion is restricted to a zone which is narrow both horizontally and vertically. There is no impact of breakers at levels lower than the troughs of the waves, though erosion may extend down to the limit of effective agitation. The



Fig. 246.— Showing blocks similar to those of Fig. 245, reduced and rounded by wave-action. Shore of Lake Champlain. The rock is Utica shale. (Perry.)

upper limit of effective wave-action is the level of the wave-crests. The rise and fall of the water during the flow and ebb of the tides gives the waves a greater vertical range than wind-waves alone would have. The indirect work of waves is limited only by the height of the shore, for as the zone of excavation is carried land-ward, masses higher up the slope are undermined and fall. The fallen rock temporarily protects the shore against the waves (Fig. 245), but the fallen masses are themselves eventually broken up.

The general result of wave-erosion is the advance of the sea on the land, the rate of advance being determined chiefly by the nature of the material attacked and the strength of the waves. Though examples of the retreat of coast-lines before the advance of the sea are numerous, it is not to be understood that the advance of the sea on the land is universal or uninterrupted. On the contrary, the land often encroaches on the sea, and the two things sometimes go on side by side. At Long Branch, N. J., the advance of the sea has been so rapid in recent years as to menace important buildings, while a few miles to the north and south, the land is advancing into the sea by the deposition of shore drift. The low coast of the

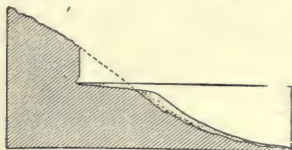


Fig. 247.

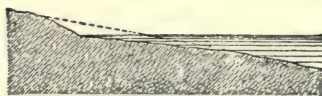


Fig. 248.

Fig. 247.— Diagram illustrating high sea cliffs. It shows also a submerged terrace, due partly to wave-cutting and partly to building.
 Fig. 248.— Diagram showing a low sea cliff.

Middle Netherlands has retreated two miles or more in historic times, but the opposite tendency is shown at other points in the same region. On the coast of England the sites of villages have disappeared by the advance of the sea within historic times¹, but the coast of the same island affords illustrations of land advance. On the south side of Nantucket Island, the sea-cliff has been known to retreat before the waves as much as six feet in a single year.² Almost every considerable stretch of coast affords illustrations both of the advance of the sea on the land and of land on the sea; but in the long run, the former exceeds the latter.

Topographic features developed by wave-erosion. As the waves cut into the shore at and near the water-level, they develop a steep slope above the line of cutting. This steep slope is the *sea-cliff* (Figs. 247 to 250). The term *lake cliff* is applied to the corresponding cliffs of lakes.

¹ Dana, *Manual of Geology*, 4th. ed., p. 219.

² Shaler, *Sea and Land*, p. 29.

The height of the cliff depends on the height of the land on which the sea is advancing. Its slope may be steep or gentle (Figs. 247 and 248), according to the nature of the material of which it



Fig. 249.— A high sea cliff, La Jolla, Cal.



Fig. 250.— A high cliff with a beach, shore of Lake Michigan. (U. S. Geol. Surv.)

is composed and the rapidity of the cutting. Rapid cutting and resistant material tend to produce steep cliffs; but incoherent materials, such as sand and clay, may form steep cliffs if the cut-

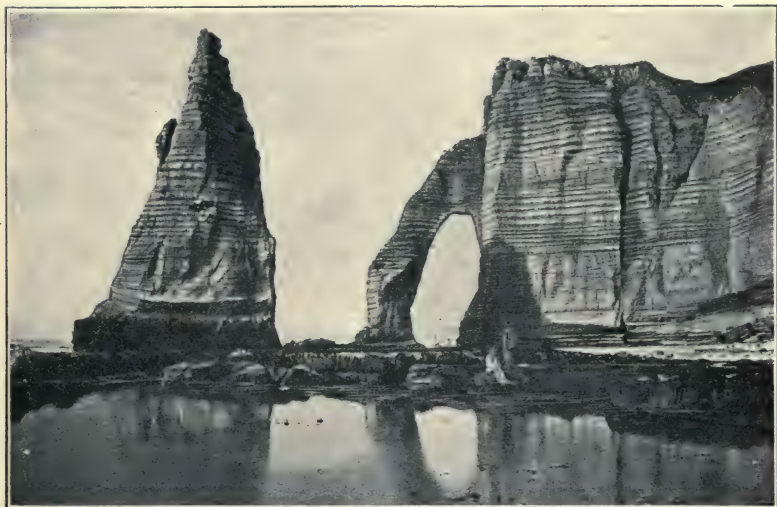


Fig. 251.— A chimney rock and an arch on the coast of France. (Neurdein.)



Fig. 252.— Chimney rocks, etc., developed by wave erosion, Coast of California. (Fairbanks.)

ting is rapid. The structure of the cliff-rock also influences the slope and configuration of the sea-cliff.

By working in along the joints of the rock, widening them and quarrying out the intervening blocks, pillars of rock ("*chimney-rocks*," "*pulpit-rocks*"), or even considerable islets are sometimes isolated by the waves (Figs. 251 and 252).

Waves sometimes excavate *caves* at the bases of cliffs. The bottom and roof of a sea-cave usually have a pronounced inclination landward, and if the cliff is low, the cave may be extended landward until its roof is pierced. Through such an opening in the top of the cliff the water of the incoming waves may be forced in the form of spray. On the New England coast, such holes are sometimes known as "spouting horns." Similar openings may be made, as already pointed out, by the compression or rarefaction of the air in the cave as the wave enters or retreats. The cave, the "spouting horn," the "pulpit-rock," and other isolated islets, are all closely associated with the sea-cliff in origin.

The bottom of the sea-cliff is bordered by a submerged platform over which the water is shallow. This platform, or at any rate its landward portion, represents the area over which the water has advanced as the result of wave-cutting, and is, therefore, known as the *wave-cut terrace*. Such a terrace is the necessary accompaniment of the cliff. Wave-cut terraces may become land by elevation, or by the lowering of the level of the sea (Fig. 253). Elevated sea-cliffs with wave-cut terraces at their bases are among the best evidences of change of relative level between water and land.

Wave-erosion and horizontal configuration. The structure of the rock along shore has much to do with the horizontal configuration of the wave-shaped coast. In general, waves develop re-entrants in the weaker portions of the shore, leaving the more resistant parts as headlands (Fig. 1, Pl. XIX). It is to be noted that the resistance of rock to wave-erosion is not determined by its hardness alone. Every division plane, whether due to bedding, to jointing, or to irregular fracture, is a source of weakness to the rock, and rock of great hardness may be so broken as to offer relatively little resistance. A coast which is regular and of equal exposure, but of

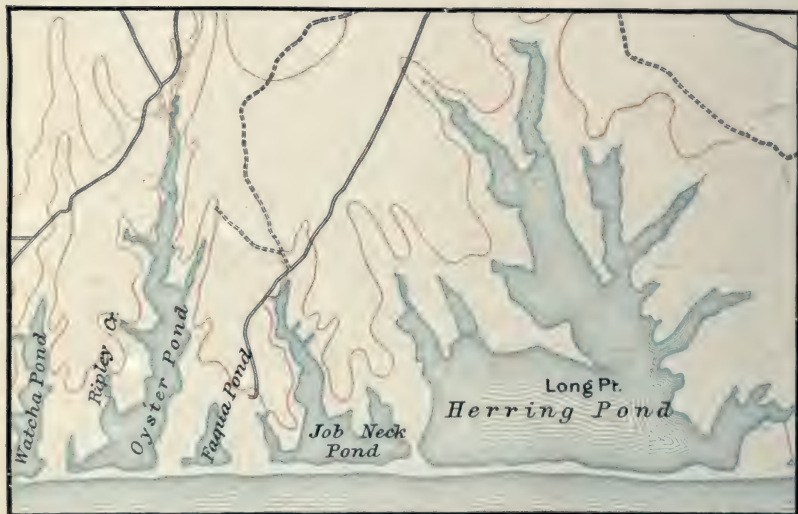


FIG. 1.—A coast line developed chiefly by wave erosion. Scale, about 1 mile per inch. (Tamalpais, Cal., Sheet, U. S. Geol. Surv.)



FIG. 2.—An island tied to the mainland by a "beach." Scale, about 1 mile per inch. (Boston Bay, Mass., Sheet, U. S. Geol. Surv.)

PLATE XX



Coastal lakes formed by the blocking of the ends of drowned valleys.
Scale, about 1 mile per inch. (Marthas Vineyard, Mass., Sheet,
U. S. Geol. Surv.)

unequally resistant material, will be made irregular by the waves. A regular coast of uniform material, but unequal exposure, will be made irregular by greater cutting at the points of greater exposure. A coast of marked irregularity and homogeneous material will be made more regular by the cutting off of the projecting points, because they are most exposed. With a given set of conditions, waves tend to develop a certain sort of shore-line which, so far as its horizontal form is concerned, is relatively stable. Such a shore-line may be said to be *mature*¹ so far as wave-erosion is concerned.



Fig. 253.— A wave-cut terrace now well above the sea. Either the land has been raised or the sea-level has sunk since the terrace was cut. Seward Peninsula, Alaska. (U. S. Geol. Surv.)

Since coastal lands are, in general, both heterogeneous and unequally exposed, a mature coast-line is somewhat irregular.

Since the conditions of erosion along coasts are constantly, even if slowly, changing, maturity is constantly being approached, but rarely reached. Other forces and processes, such as those of aggradation, vulcanism, and diastrophism, are in operation along coasts, and their results are sometimes antagonistic to those of the waves. The horizontal configuration of coasts is, therefore, the result of many co-operating forces, of which waves are but one. It is, nevertheless, important to note the end toward which the waves are working, even though they are continually defeated in their

¹ Gulliver, *Shore Line Topography*; Proc. Am. Acad. Arts and Sci., Vol. XXXIV, 1899, pp. 151–258. A valuable study of shore-line topography.

attempt to reach it. Their immediate goal is maturity of configuration; their final goal is the destruction of the land and the deposition of its substance in the sea.

Transportation. The material eroded from the shore by the waves is transported by the joint action of waves, undertow, and shore-currents.

The incoming wave begins to shift material where it begins to drag bottom. From the line where transportation begins, to the line of breakers, detritus at the bottom is shifted toward the shore by the waves, while the undertow tends to carry it back again. The result of these opposed tendencies is to keep sediment moving back and forth between the shore and the line of breakers. The advance and retreat of waves which come in at right angles to the shore do not move sediment along the shore; but oblique waves and littoral currents shift it along shore. The direction of movement is readily inferred from Fig. 244. The direction in which debris is shifted by waves and shore-current is modified by the undertow, and the direction which would result from undertow and current is modified by the wave. It is often the waves of storms, rather than those of the prevailing winds, which determine the direction of greatest shore transportation.

The waves, the undertow, and the littoral currents work together in assorting the detritus of the shore. If the coarsest parts are beyond the power of all but the strongest waves, they accumulate where agitation is great. Less coarse parts are carried farther from the site of greatest agitation, but no materials which are classed as coarse are carried beyond the depth of sensible movement. The coarse material which covers the bottom where the agitation of the water at the bottom is effective, constitutes *shore drift*, whether derived from the shore by the waves, or brought to the sea by streams.

The material which is fine enough to be held in suspension is measurably independent of depth. This is shown during storms when the water becomes turbid far beyond the line of breakers, and clears only after the waves have died away.

The sorting of shore drift, effected while it is in transportation, is often very perfect. The conditions favoring assortment are (1)

vigorous wave-action, (2) prolonged transportation, and (3) a moderate volume of sediment.¹

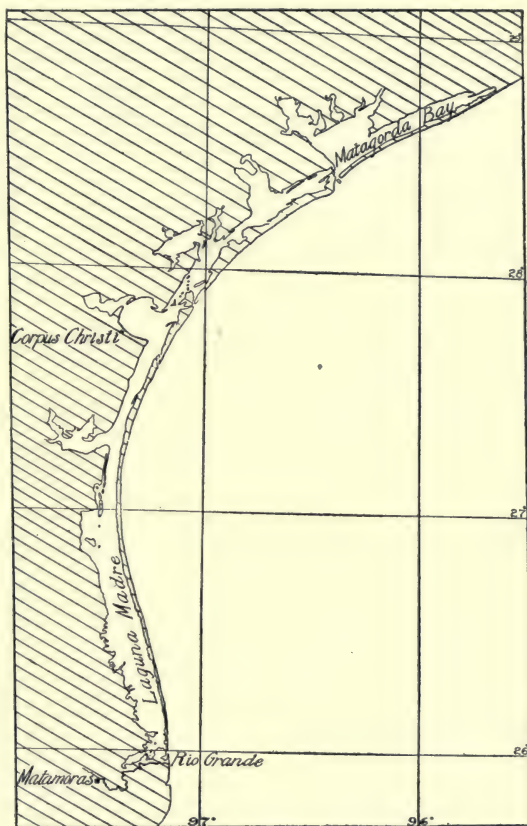


Fig. 254.—A portion of the Texas coast, showing the tendency of shore-deposition to simplify the coast line. The deposits (the narrow necks of land parallel to the coast) shut in the bays. (From chart of C. and G. Surv.)

Deposition by waves, undertow, and shore-currents. The zone occupied by the shore drift in transit is the *beach*. Its lower margin is beneath the water, a little beyond the line where the great storm-waves break. Its upper margin is at the level reached by storm-

¹ Willis, Jour. of Geol., Vol. I, p. 481.

waves, and is usually a few feet above the level of still water. Material is brought to the beach from seaward by incoming waves, and from it detritus is carried out by the undertow. The cross-section of a beach is shown in Fig. 255. The beach follows the general boundary between water and land, though it does not con-

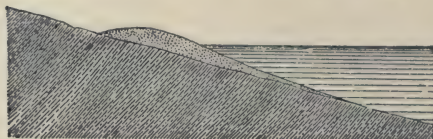


Fig. 255.— Cross-section of a beach. (Gilbert.)

form to its minor irregularities (Figs. 240 and 254). The beach (or barrier) often causes the deflection of the lower courses of streams descending to it.

In its deposition, the shore drift assumes various forms. Where the bottom near shore has a very gentle inclination, the incoming waves break some distance from the shore-line, and it is here that the most violent agitation occurs when the waves are strong. To this line of breakers, material is shifted from both directions. Accu-

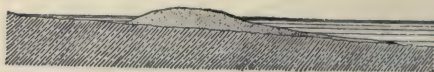


Fig. 256.— Section of a barrier. (Gilbert, U. S. Geol. Surv.)

mulating here, it builds up a low ridge, called the *barrier* (Fig. 256). If it is built up above the surface of the water by storm-waves, it may shut in a lagoon behind it, and this may ultimately be filled by sediment washed down from the land. At one stage in the filling, the lagoon becomes a marsh (Fig. 258).

The disposition of shore deposits depends largely on the currents at and near shore. If the coast-line is deeply indented, the littoral current usually fails to follow the re-entrants. In holding its course across the mouth of a small bay, a shore-current usually passes into deeper water. Here its velocity is checked because its motion is communicated to the water beneath it, and, a larger amount of



Fig. 257.— An elevated barrier beach on the coast of California.

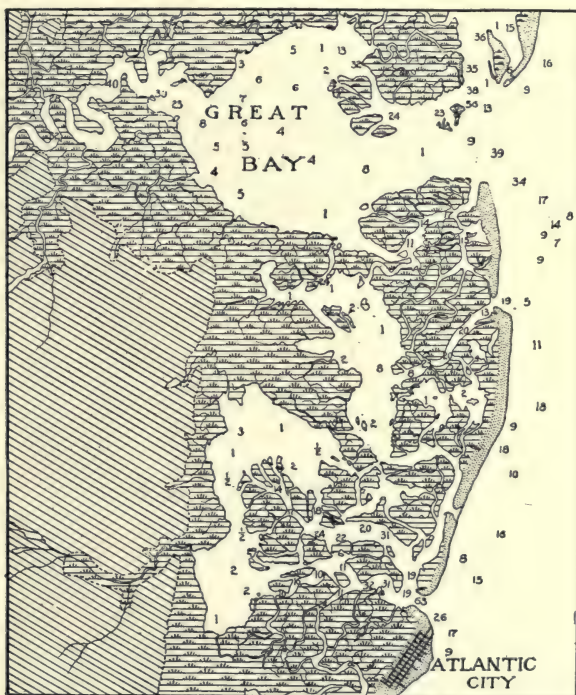


Fig. 258.— Sketch-map of a part of the New Jersey coast. The dotted belt at the east is the barrier, modified by the wind. The area marked by diagonal lines is the mainland; the intervening tract is marsh-land. The numbers show the depth of water in feet. Scale: $\frac{1}{4}$ inch = 1 mile.

water being involved in the motion, the motion of each part is diminished. If sediment was being moved along its bottom before the current was checked, some part of it is dropped when and where the current is slackened. It follows that deposition commonly takes place beneath a littoral current as it crosses the mouth of a bay. The belt of deposition is often narrow, and the result is the construction of a ridge beneath the water in the direction of the current. The current would never build the embankment up to the water-level, but when its surface approaches the level of effective agitation, the waves may build it up to, and even above



Fig. 259.— A recurved spit, Dutch Point, Grand Traverse Bay, Lake Michigan. (U. S. Geol. Surv.)

the surface of the water. So long as the end of such an embankment is free, it is a *spit*. The construction of a spit has been aptly compared to the construction of a railway embankment across a depression. The material is first carried out from the bordering upland (in this case the shallow water) and dumped where the slope to the depression (deep water) begins. The embankment thus begun is extended by the carrying out of new material, which is left at the end of the dump already made, as at the end of a railway grade.

The spit is normally either straight or parallel with the general course of the shore-current, but since the littoral current is subject to change with the shifting of the winds, the spit may depart from straightness. Winds which simply reverse the direction of the littoral current retard its construction; but if a strong current

flows past the end of a spit, it may cut away its extremity and rebuild the materials into a smaller spit, joining the main one at an angle. This gives rise to a *hook* (Fig. 259). Successive storms may develop successive hooks along the side of a growing spit. The end of a hook may be so extended as to join the mainland, when it becomes a *loop*. If the spit is lengthened until it crosses, or nearly crosses, the bay, shutting it off from the open water, it



Fig. 260.— Map of the head of Lake Superior. (U. S. Geol. Surv.)

becomes a *bar*. Bars have shut in lakes (ponds) on the coast of Martha's Vineyard, Mass. (Pl. XX), and lakes, ponds, and lagoons at numerous points both on the Atlantic and the Pacific coasts. The same phenomena are to be seen along many lake shores (Fig. 260). Bars sometimes tie islands to the mainland (Pl. XIX, Fig. 2).

If the bay across which the bar is built receives abundant drainage from the land, the outflow from the bay may be sufficient to prevent the completion of the bar, for when the growth of the bar has sufficiently narrowed the outlet of the bay, the sediment brought to the end of the spit by the littoral current will be swept out beyond the spit by the current setting out from the bay. The completion of a bar may be interfered with also by tidal currents,

even without land-drainage. The scour of the tides often preserves deep entrances (inlets) to bays, and maintains definite channels or "thorofares" in the lagoon marshes behind barriers and spits. The sediment brought down from the land, as well as that washed in by tidal currents and waves, tends to fill up the lagoon behind a barrier, a spit, or a bar, converting it into land (Fig. 258).

Since spits and bars are built only where there is shore-drift in transit, they are always built out from a beach or barrier. The distal end of the bar may also join a beach or barrier. Traced back to its source, the beach from which a spit leads out is often found to terminate in the cliff from which the material of the beach and the spit were derived. In such cases the sediment of the beach has been shifted but a short distance; but in other cases it has traveled far.

The off-shore movements of shore-waters may leave the sediment of the shore in the form of a *wave-built terrace*, which is really a seaward extension of the beach. The wave-built terrace often borders the wave-cut terrace along its seaward margin (Fig. 247). Terrace-cutting and terrace-building are both involved in the development of the continental shelves.

Beach ridges, spits, bars, etc., like sea-cliffs and wave-cut terraces, are often preserved after the relative level of sea and land has changed. If the shore has risen, relatively or absolutely, these features are evidence of the change. If shore features are submerged instead of elevated, they furnish less accessible though not less real evidence of the change of level. Similar features about lakes have a like significance, but in this case it is often demonstrable that it is the water rather than the land which has changed its level.

Effect of shore-deposition on coastal configuration. The tendency of shore-deposition is to cut off bays and to straighten and simplify the shore-lines. This is abundantly illustrated along the Atlantic and Gulf coasts of the United States (Figs. 240, 254, and Pl. XX). It is to be noted, however, that in the simplification of the shore-line through deposition, the initial stages often result in great irregularity (Fig. 254 and Pl. XIX, Fig. 2).

¹ For map work on topographic features of shores, see end of Chapter.

The Work of Ocean-currents

As agents of erosion, ocean-currents are not of great importance. Currents which reach the bottom are comparable, in their effects, to rivers of the same velocity and volume; but most ocean-currents do not touch bottom, and therefore do not erode it. Only where they flow through narrow and shallow passageways is their abrasive work considerable. Thus the Gulf Stream has a velocity of four or five miles per hour where it issues from the Gulf, and its shallow and narrow channel is current-swept. The abrasive power of the Gulf Stream is known to continue somewhat beyond its narrow channel, for on the Blake Plateau (between the Bahamas and Cape Hatteras), where the water is 600 fathoms and less in depth, "the bottom of the Gulf Stream . . . is swept clean of lime and ooze and is nearly barren of animal life."¹ Other illustrations of the erosive power of currents have been noted near Gibraltar in water 500 fathoms deep, and between the Canary Islands at depths of 1000 fathoms.² In spite of these examples, and of many others which probably exist in similar situations, it yet remains true that ocean-currents are on the whole but feeble agents of erosion.

Ocean-currents are scarcely more important in transporting than in eroding, for they carry little except that which they erode, if the life which inhabits them is left out of consideration. Currents which do not touch bottom roll no sediment, and carry only what may be held in suspension. A river's power of transporting sediment in suspension is due largely to cross-currents occasioned by the unevenness of its resistant bottom. If a particle of mud in suspension in a river drops to the bottom, as it frequently does, it may be picked up again and carried forward. If, on the other hand, a particle in suspension in an ocean-current once escapes the moving water by settling through it, the current which does not drag bottom has no chance to pick it up again. Very fine sediment may be carried by an ocean-current far beyond the point where it was acquired, but currents which do not touch bottom

¹ Agassiz, *Three Cruises of the Blake*, Vol. I, p. 259. Agassiz would ascribe the Blake Plateau itself to the Gulf Stream, p. 138. See also *Am. Jour. Sci.*, Vol. XXXV, 1888, p. 498.

² Reade, *Phil. Mag.*, Vol. XXV (1888), p. 342.

are rarely strong enough to hold any but the finest material for any considerable length of time. As transporters of sediment, therefore, ocean-currents are at a great disadvantage as compared with rivers.

How readily particles of extreme fineness may be kept in suspension, and how little agitation is necessary to keep them from sinking, is shown both by experiment and observation. Experiment has shown that fine particles of clay require days to settle a foot in still water, and the Challenger found fine sediment derived from the land 400 miles from the coast of Africa. Sediment settles more readily in salt water than in fresh, despite the fact that the former is heavier. This is presumably because the salt diminishes the cohesion of the water.¹

Deposition by ocean-currents is limited by their transportation. Only where they erode their bottoms do they gather coarse materials, and only in the lee of such places are their deposits coarse. Since the material which they carry is generally fine, it is widely distributed before deposition.

DEPOSITS ON THE OCEAN-BED

The deposits on the bed of the ocean may be divided into two classes according to the depth of water in which they are made.² *Shallow-water deposits* are made in water less than about 100 fathoms deep, and *deep-sea deposits* are laid down in water of greater depth. The selection of the 100-fathom line as the dividing depth is less arbitrary than it seems, for passing outward from the shore, it is at about this depth that the bottom ceases to be commonly disturbed by the action of currents and waves; that sunlight and vegetable life cease to be important at the bottom; and that the coarser sediments which predominate along shore give place, as a rule, to muds and oozes. Furthermore, the 100-fathom line (or some line very near it) is an important one in the physical relief of the globe, for it appears to mark, approximately, the junction

¹ The reason usually assigned is the "flocculation" of the fine sediment, but there is reason to doubt this explanation.

² Murray, Challenger Report, Deep Sea Deposits, pp. 184, 185.

of continental plateaus and ocean-basins. Because the latter are a little overfull, the water runs over their rims, covering about 10,000,000 square miles of the borders of the continental protuberances.

Aside from the deposits made by organisms, shallow-water deposits are divisible into two groups — (1) those immediately along the shore, the *littoral deposits*, and (2) those made between the littoral zone and the 100-fathom line. Both are terrigenous chiefly, though chemical and organic deposits occur in both zones. The deep-sea deposits likewise are divisible into two principal groups, (1) the *terrigenous deposits* near the land, and (2) the *pelagic deposits*, made up chiefly of the remains of pelagic organisms, and the ultimate products arising from the decomposition of rocks and minerals. The former predominate in the less deep waters relatively near shore; the latter in the deeper water far from land. The shallow- and deep-water deposits grade into each other in a belt along the 100-fathom line.

Shallow-water Deposits

Littoral deposits. The littoral zone is often defined as the zone between high- and low-water marks, but in common speech, the very shallow water a little farther from the coast-line is often included. It is the zone in which boulders, gravels, sands, and all coarser materials accumulate, though muds are occasionally met with in sheltered estuaries. Generally speaking, the nature of these deposits is determined by the character of the adjoining lands and the nature of the local organisms. The heavier materials brought down by rivers or worn from the shore by waves are here spread out by waves and shore-currents. Twice in the twenty-four hours the littoral zone is covered by water, and twice parts of it are exposed to the direct rays of the sun or the cooling effects of the night. Physical conditions in general are here most varied. Still greater diversity is introduced by the fact that the zone is inhabited by both marine and terrestrial organisms, while the evaporation of the sea-water which flows over tidal marshes and lagoons leads to the formation of saline deposits. The length of the coast-lines of the world is some 125,000 miles (about 200,000

kilometers), so that the zone of littoral deposits, though narrow, covers a very considerable area.

Mechanical deposits in shallow water beyond the littoral zone.

These deposits are made between the littoral zone and the 100-fathom line, and cover an area of about 10,000,000 square miles.¹ Their composition is much the same as that of the littoral deposits with which they are continuous, except that they are finer. At their lower limit they pass insensibly into the fine deposits of the deep sea. Coarse materials, such as gravel and sand, prevail, though in depressions and inclosed basins, and out toward the oceanward edge of the zone, muddy deposits are found. Some of the deposits are composed wholly of inorganic debris, but organic

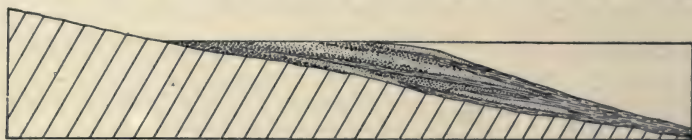


Fig. 261.— Diagram showing the interwedging of gravel, sand, and mud beds.

remains are freely mingled with others. The mechanical effects of tides, currents, and waves are everywhere present, but become less and less well marked as the 100-fathom line is approached. The forms of vegetable and animal life are numerous, though the former decrease as depths which make the sunlight feeble are approached.

As a rule, no definite line marks the seaward terminus of the coarse detritus, since coarse material is carried farther out when the waves run high (and the undertow is strong) than when they are feeble. In calm weather, therefore, fine sediment may be deposited where coarse had been laid down in the preceding storm, only to be covered in turn by other deposits of a different character. Thus gravel grades off into sand, with more or less overlapping or interwedging, and sand grades off into silt in the same way. This is diagrammatically illustrated by Fig. 261.

Since coarse deposits may extend far out from land where the waves are strong and the water shallow, and since the zone of

¹ Murray, *loc. cit.*, pp. 187-188.

shallow water may be extended seaward by the aggradation of the bottom, shallow-water deposits may cover extensive areas. They may become deep at the same time, for as the outer border of the

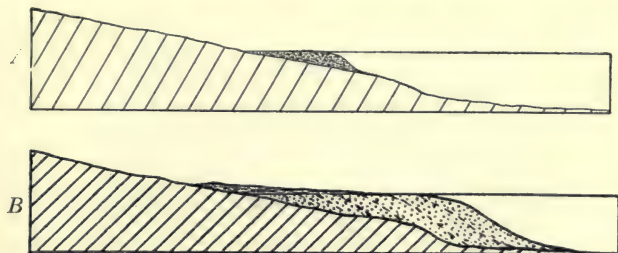


Fig. 262.— Diagrams showing how shallow-water deposits may attain considerable depth by the shifting of the zone of deposition seaward.

shallow-water zone is shifted seaward by aggradation, the vertical space to be filled becomes greater (compare *A* and *B*, Fig. 262). Again, if the coast is sinking, new deposits of coarse material may be made on older ones. In this way, also, great thicknesses of sediment may be accumulated, all parts of which were deposited in shallow water. The great thicknesses of some of the conglomerate beds of the past show how far this process may go.



Fig. 263.— Ripple-marks.

Characteristics of shallow-water deposits. Clastic sediments laid down in shallow water have several distinctive characteristics. While they are, in the aggregate, coarse, they are characterized by frequent variations in coarseness. The surfaces of successive beds are likely to be ripple- and rill-marked (Figs. 263 and 264),

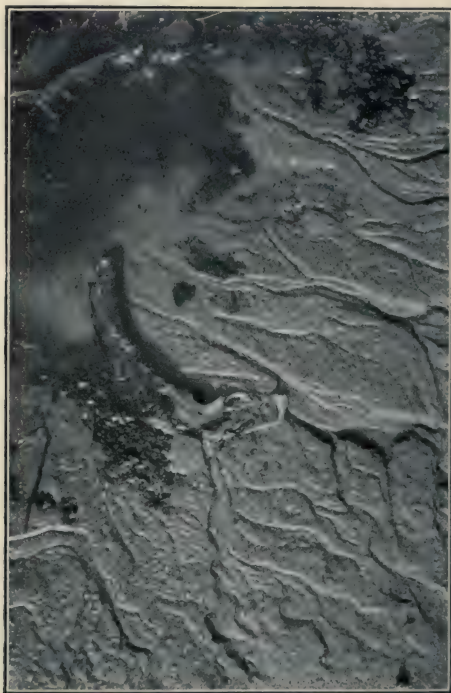


Fig. 264.— Rill-marks resembling impressions of seaweeds. Beach at Noyes Point, R. I. (Walcott, U. S. Geol. Surv.)

and cross-bedding (Figs. 265 and 266) is common. Clayey sediments accumulated between high and low water are often sun-cracked (Figs. 267 and 268), and the tracks of land animals are sometimes preserved on their surfaces. Shallow-water deposits often contain fossils of organisms which live in waters of slight depth. These characteristics are sufficient to differentiate sedi-

mentary formations made in shallow water from those made in deep water, even after they have been converted into solid rock, and after the rock has emerged from the sea. Many of these char-

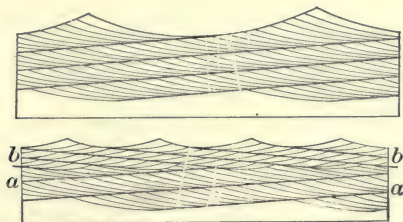


Fig. 265.— Cross-bedding. (Gilbert).

acteristics are, however, shared by deposits made by streams on land. Subaërial and lacustrine sediments are usually distinguishable from those made in the sea by their fossils, and sometimes by their distribution.



Fig. 266.— Cross-bedded sandstone, Dells of the Wisconsin. The strata are horizontal. The laminae within each stratum dip notably. (Atwood.)

Topography of shallow-water deposits. The shallow-water deposits have, on the whole, a rather plane surface, though there are some notable departures from flatness. The steep slopes of the delta fronts and of wave-built terraces have already been spoken of. Barriers often shut in depressions, and the disposition of the



Fig. 267.— Sun-cracks. Flat of the Missouri River a few miles above Kansas City. The sun-cracks on shore deposits are not essentially different. (Calvin.)

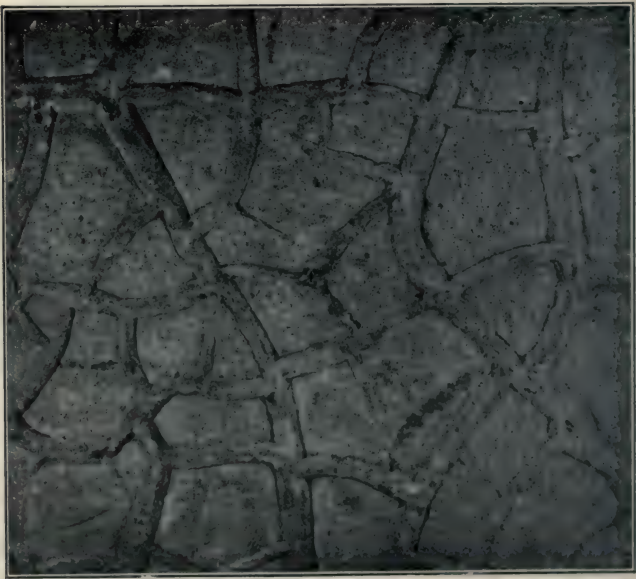


Fig. 268.— Sun-cracks in sandstone. About three-eighths natural size. (Geikie.)

material deposited is sometimes uneven, owing to shore and tidal currents. The result is that the surface of the shallow-water deposits is often affected by low elevations and shallow depressions. The elevations and depressions may be elongate, circular, or irregular in form. This topography is sometimes preserved on newly emerged lands.

Chemical and organic deposits in shallow water. There is no sharp line of distinction between the deposits usually classed as chemical and those classed as organic. The latter are chemical in the broader sense of the term, but as they are immediately associated with life and are dependent upon it, it is a matter of practical convenience to separate them. Aside from the organic deposits, the chemical deposits made in shallow sea-water embrace (1) those due to evaporation, and (2) those due to chemical reactions between constituents so brought together that new and insoluble compounds are formed and precipitated.

The chemical deposits made in the shallow water of the sea, or in bodies of shallow water isolated from the sea, are chiefly simple precipitates resulting from evaporation. All substances in solution are necessarily precipitated on complete evaporation; but since the sea-water is in general far from saturation, so far as all its leading salts are concerned, only a few are thrown down in quantity sufficient to be of geological importance where evaporation is incomplete. The principal deposits of this sort are calcium carbonate (limestone, CaCO_3) and sulphate (gypsum, $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$), common salt (rock salt, NaCl), and the magnesium salts, usually the chlorides or sulphates.

While there is more than ten times as much lime sulphate as lime carbonate in the ocean (p. 289), deposits of the carbonate (including shells, coral, etc.,) have been very much greater than those of the sulphate. This is due to the following facts: (1) The sulphate is much more soluble in natural waters than the carbonate, (2) rivers bring much more carbonate than sulphate to the sea, and (3) marine plants and animals extract lime carbonate from the water for their skeletons, shells, etc. The secretion of lime carbonate by organisms is not dependent on the saturation of the water, but may be carried on when the amount in solution is very small.

The chief deposits of *lime carbonate* have been made through the agency of plants and animals, in the form of shells, coral, bones, teeth, and other devices for supporting, housing, protecting, and arming themselves; but while it is agreed that the larger part of the lime carbonate deposited in the open sea is of organic origin, it is equally clear that in closed seas subject to concentration from evaporation, simple precipitation may take place. There is difference of opinion as to the quantitative importance of this last class of deposits.

Gypsum appears to be deposited in quantity only in the basins of arid regions where concentration reaches an advanced state. Since normal sea-water is far from saturation with *common salt*, the latter is precipitated only in lagoons, in closed seas, or other situations favorable to great concentration. This is, as a rule, only in regions which are notably arid. It follows that deposits of salt usually signify highly arid conditions, and where they occur over wide ranges in latitude and longitude, as in certain periods of the past, general aridity of climate is inferred. Where confined to limited areas, their climatic significance is less, for topographic conditions may determine local aridity. The total area where salt is now being precipitated is small, though on the whole the present is probably a rather arid period of the earth's history. On the other hand, ancient deposits of salt preserved in the sedimentary strata show that the area of salt deposition has been much more considerable than now at one time and another in the earth's history. The salt and gypsum deposits of the past seem, therefore, to tell an interesting tale of the climates of the past.

The *magnesium salts* are among the last to be thrown down as the sea-water is evaporated, and they most commonly take the form of sulphates and chlorides. They often form double salts with potassium, a relatively small and soluble constituent of sea-water. In the artificial evaporation of salt water to obtain common salt, the process is usually stopped before the saturation point for the magnesium salts is reached, and the residue, the "mother-liquor," or "bittern," is drawn off to prevent these "bitter" salts from mixing with the common salt. The magnesium salts are among the last to be precipitated, not only because they are readily soluble,

but because their quantity is small; yet in the original rock from which the sea-salts came, there is at least as much magnesium as sodium, while in the sea there is about five times as much sodium as magnesium. Just what becomes of all the magnesium in the sea-water is not well understood. In the earlier marine strata, *dolomite*, composed partly or wholly of the double carbonate of lime and magnesia (CaMgCO_3), abounds. This appears to have been formed by a gradual substitution of magnesium for calcium, in calcium carbonate, but just how and when and why the substitution was effected is not fully understood.

The plants and animals of the sea secrete notable quantities of silica. Deposits of this sort are relatively more important in the deep sea than in shallow water, and will be mentioned in that connection.

Limestone. Something concerning the origin of limestone has already been given in the preceding paragraphs; but because of the importance of this formation, it may be added, by way of summary, that shallow seas free or nearly free from terrigenous sediment, and abounding in lime-secreting life, furnish the conditions for nearly pure deposits of limestone, and that most of the limestone within the areas of the present continents appears to have originated under such conditions. The common notion that limestone is normally a deep-water formation is a serious error. Although limestones are formed in deep as well as in shallow waters, the more important classes of lime-secreting organisms are limited to the depths to which light penetrates. In the shallow waters, these plants and animals are in part free and in part attached. Within the areas of deep water, they are free and at the surface, and their remains drop to the bottom if not sooner dissolved. But few forms live on the deep, dark, cold bottoms of the abysmal depths. Clear waters, free from abundant terrigenous sediments and abounding in lime-secreting life, rather than deep waters, are, therefore, the most favorable conditions for the origin of limestone.

The purely chemical deposits of limestone are probably all of shallow-water origin. Once made, they are subject to solution, re-deposition, and other mutations like other deposits. As a result,

they often lose many of their original characteristics, but enough usually remain to tell the story of their origin.

Deep-sea Deposits

Contrasted with shallow-water deposits. The deep-sea deposits cover the ocean-bottom below the 100-fathom line. Their area is considerably more than half the earth's surface. The characteristic deposits are muds, organic oozes, and clays, which, in their physical characteristics, are remarkably uniform. Gravels and sands are rarely found. In regions of floating ice, some diversity is introduced from the varied nature of the materials which it transports. Vegetable life is limited to the surface waters, while animal life is present in them and on the bottom, but absent or nearly so in the great middle zone between. The temperature of the bottom is below 40° Fahr. throughout the larger part of the ocean, and subject to little variation. The conditions over the sea-bottom are therefore very uniform.

In consequence of the slow accumulation of sediment on the deep-sea bottom, the absence of transportation there, and the nature and small size of the particles, many evident chemical reactions take place, resulting in the formation of many secondary products, such as glauconite, phosphatic and manganic nodules, zeolites, etc. The amount of matter arising from the decomposition and alteration of minerals and rocks increases, relatively, with increase of distance from the land. At the same time there is an increase (relative), in all moderate depths, of the remains of pelagic organisms. We thus pass insensibly from deep-sea deposits of a terrestrial origin (*terrigenous deposits*) near the land, to *pelagic deposits*, "in which the remains of calcareous and silicious organisms, clays, and other substances of secondary origin play the principal rôle."¹

The following table ² shows the relations of the various groups of marine deposits.

¹ Murray, Challenger Rept., Deep Sea Deposits.

² Ibid., p. 186.

1. Deep-sea deposits beyond 100 fathoms.....	{ Red clay Radiolarian ooze Diatom ooze Globigerina ooze Pteropod ooze Blue mud Red mud Green mud Volcanic mud Coral mud	I. Pelagic deposits formed in deep water, removed from land
2. Shallow-water deposits between low-water mark and 100 fathoms	{ Sands, gravels, muds, etc.	II. Terrigenous deposits formed in deep and shallow water, mostly close to land
3. Littoral deposits between high- and low-water marks	{ Sands, gravels, muds, etc.	

In spite of this classification of Murray, the coral and volcanic muds cannot be regarded as terrigenous, and shells, coral, etc., are found abundantly in shallow-water deposits. It is to be noted that the pelagic deposits are partly inorganic and partly organic in origin. The inorganic materials may be of mechanical or chemical origin.

Mechanical inorganic deposits. The mechanical deposits of the deep sea come (1) from the land by the ordinary processes of gradation, (2) from volcanic vents, and (3) from extra-terrestrial sources. The terrigenous materials which reach the deep sea are, as a rule, only the finest products of land decay, and are carried out by movements of water and by winds. They are not commonly recognized in the dredgings more than 200 miles from shore, but opposite the mouths of great rivers they extend much farther,—1,000 miles in the case of the Amazon. They are especially abundant on the slopes of the continental shelves, where the *blue*, *green*, and *red muds* are associated with volcanic and coral muds. The color of these various muds depends in part on the changes they have undergone since their deposition. The green muds usually contain enough glauconite to give them their color, and are most commonly found off bold coasts where sedimentation is not rapid. The blue muds indicate lack of oxidation, or perhaps deoxidation. Red muds are not common, though found in some situations. These deposits are analogous, in a general way, to certain shales, marls, etc., found on the continents.

The occasional presence of coarse materials derived from the land in the deep-sea deposits must be looked upon as in some sense accidental. Pebbles, or even boulders, entangled in the roots of floating trees, may be carried out into the ocean, and icebergs carry out boulders and smaller fragments of rock. The amount which icebergs might carry, if fully loaded, is far greater than the amount which they do carry.

Of the identifiable inorganic materials among the pelagic deposits, those of volcanic origin are most abundant, and among these the most common is pumice, which often floats readily until it becomes waterlogged. Pieces of pumice brought up from the bottom and thoroughly dried, will float for months in sea-water. The next most abundant substance of volcanic origin in pelagic deposits is *volcanic glass*. This ranges from pieces of the size of a walnut down to the smallest fragments, which often serve as centers for concretions. *Lapilli* (cinders) and *volcanic ash* also abound in parts of the deep sea. The distribution of these volcanic products is essentially universal, though by no means uniform. Some of them are probably from submarine volcanoes.

The deep-sea deposits contain many nodules and grains which are believed to be of extra-terrestrial origin. Many of them are magnetic.¹ The dust of the countless meteors which enter the atmosphere daily settles on land and sea alike, and must enter into the sediment at the bottom of the latter. It is probably no more abundant in deep water than in shallow, but it is relatively more important, since other sedimentation is meager. The number of meteorites which enter the atmosphere daily has been estimated at from 15,000,000 to 20,000,000.² If, on the average, the meteorites weigh ten grains each, probably a rather high estimate, the total amount of extra-terrestrial matter reaching the earth yearly would be 5,000 to 7,000 tons, and something like three-fourths of this must, on the average, fall into the sea. But even at this rate it would take some fifty billion years to cover the sea-bottom with a layer one foot in thickness.

¹ Challenger Report, Deep Sea Deposits, p. 327.

² Young's Astronomy, p. 472.

Organic constituents of pelagic deposits. With increasing distance from shore, and especially with increasing depth of water, terrigenous deposits become less and less abundant, and sediments derived from pelagic life increase in relative importance. Beyond the upper part of the outer slopes of the continental shelves, the deep-sea deposits are made up largely of the secretions of marine organisms which live in the surface-waters. Pelagic molluscs, foraminifera, and algæ secrete lime carbonate, while diatoms and radiolarians secrete silica. When the organisms die, they sink to the bottom and their secretions are mingled with the volcanic and other materials which are universal over the sea-floor.

Pelagic deposits of organic origin are named according to their characteristic constituents. Thus there are *pteropod oozes*, *globigerina oozes*, *diatom oozes*, *radiolarian oozes*, etc. It is not to be understood that these oozes are made up exclusively of the shells which give them their names. Diatom ooze is an ooze in which the secretions of diatoms are abundant, not an ooze made up wholly of these secretions; and globigerina ooze is an ooze in which globigerina shells are abundant, though in many cases they do not make up even the bulk of the matter. While samples of these various oozes might be selected which are thoroughly distinct from one another, there are all gradations between them, since pelagic life does not recognize boundary lines.

It is a significant fact that with increasing depth the proportion of lime carbonate in the ooze decreases. Thus in tropical regions remote from land, where the depths are less than 600 fathoms, the carbonate of lime of the shells of pelagic organisms may constitute 80% or 90% of the deposit. With the same surface conditions, but with increasing depth, the percentage of lime carbonate decreases, until at 2,000 fathoms it is less than 60%; at 2,400 fathoms, 30%, and at 2,600 fathoms, 10%. Beyond this depth there are usually no more than traces of carbonate of lime. The data at hand show that the percentage of lime carbonate falls off below 2,200 fathoms more rapidly than at lesser depths. When the percentage of lime carbonate becomes very low, the calcareous oozes grade off into the *red clay* with which the sea-floor below 2,400 to 2,600 fathoms is covered.

Chemical deposits. The chemical deposits of the deep sea are chiefly the alteration products of sediments which reach the sea-bottom by mechanical means. All sediment deposited in the sea undergoes more or less chemical change, but it is only when the change is very considerable that the product is referred to this class. Where sedimentation is rapid and the sediment coarse, the chemical change is relatively slight; but where the sedimentation is slow and the sediment fine, the chemical change is relatively great; for both the longer exposure to the sea-water and the greater proportion of surface exposed to attack, favor change.

The *red clay* already referred to belongs to this class of deposits. Its origin has been the subject of much discussion. It contains much volcanic debris, various concretions, bones of mammals, zeolitic crystals, and extra-terrestrial spherules, and doubtless the insoluble parts of the shells of pelagic life; but it is still a mooted question how far the clay itself is the product of decomposed shells, and how far the altered product of pulverized pumice, volcanic ash, dust, etc. Pelagic life does not seem to be less abundant at the surface where the water is deep than where it is shallow, and it would appear that the shells must sink in such situations as elsewhere. If the lime carbonate of globigerina ooze is removed by dilute acid, the inorganic residue is similar to the red clay in the ocean-bottom. This suggests that owing to the more complete solution in the very deep water, the lime carbonate of the shells has been dissolved, leaving as a residuum material which makes up a part of the red clay. The more complete solution at the bottom might be the result either of the greater pressure, or of a greater percentage of CO_2 in the water due to emanations from the sea-floor, or to both; but the rather sudden transition from oozes to red clay, with increasing depth, does not seem to be fully explained by these assumptions. The study of the dredgings has inclined the students of these materials to the conclusion that volcanic materials, rather than shells, are the principal source of the red clay.¹ The volcanic materials are thought to have accumulated slowly, and to have been long exposed to the action of sea-water.

¹ Murray, Challenger Report on Deep Sea Deposits, p. 337 et seq., and Buchanan, Proc. Roy. Soc. Edin., Vol. XVIII, pp. 17-39.

The various nodules and crystals in the clay are believed to be secondary products, the materials for which were derived from the decomposition of the sea sediments. Eolian dust, or the materials derived from it by chemical alteration, is doubtless a constituent of the red clay.

It is a significant fact that deposits corresponding to those of the deep sea have not been identified with certainty among the rock formations of the land. If such deposits are really absent from the land, as they seem to be, their absence must mean that the continents have never been beneath *deep seas*. That large parts of them have been beneath shallow sea-water is abundantly attested.

Map work. The topographic features of shores find ample illustration on maps. The Topographic Sheets of the U. S. Geological Survey listed on page 335 of the junior author's *Physiography* afford good illustrations. So also do Plates CXXX to CLIV of Professional Paper 60, U. S. Geological Survey.

CHAPTER VIII

LAKES

Many of the phenomena of the ocean are repeated on a smaller scale in lakes. The waves of lakes and their attendant undertows and littoral currents are governed by the same laws and do the same sort of work as the corresponding movements of the ocean. Tides are absent, or insignificant; but slight oscillations of level, known as *seiches*,¹ have been observed in many lakes. They are probably caused, in most cases, by sudden changes in atmospheric pressure. While they are generally very slight, they sometimes amount to as much as a foot, and occasionally to several feet. The *seiches* are oscillatory movements, and their period is influenced by the size and depth of the lake. They have been studied most carefully in Switzerland. Currents corresponding to those of the ocean are slight or wanting in lakes, but since most lakes have inlets and outlets, their waters are in constant movement toward the latter. In most cases this movement is too slow to be readily noted, or to do effective work either in corrasion or transportation. The work of ice is relatively more important in lakes than in the sea.

Changes taking place in lakes. The processes in operation in lakes are easily observed and readily understood. (1) The waves wear the shores, and the material thus derived is transported, assorted, and deposited as in the sea, and all the topographic forms resulting from erosion or deposition along the seacoast are reproduced on their appropriate scale in lakes. (2) Streams bear their burden of gravel, sand, and mud into lakes and leave it there. (3) The winds blow dust and sand into the lakes, and in some places pile the sand up into dunes along the shores. (4) Animals of

¹ Forel, *Compte Rendu*, 1875, 1876, 1878, 1879, and P. DuBois, 1891. Also Forel's *Lac Leman*.

various sorts live in the lakes, and their shells and bones give rise to deposits comparable to the animal deposits in the sea. (5) Abundant plants grow in the shallow water about the borders of many ponds and lakes, and as they die, their substance accumulates on the bottom. (6) At the outlet, the water is constantly lowering its channel. The lowering of the outlet is often slow, especially if the rock is coherent, for the outflowing water is usually clear, and therefore inefficient in corrasive work. These six processes (except the last, which does not apply to lakes without outlets) are essentially universal, and all conspire against the perpetuity of the lakes. (7) In lakes where the temperature is low enough for ice to be formed, it crowds on the shores and develops phenomena peculiar to itself (Figs. 183-4). The ice of the sea may work in similar ways, but its work is restricted to high latitudes. (8) In lakes in arid regions, deposits are often made by precipitation from solution.

The first five and the last of these processes are filling the basins of the lakes. As sediment is deposited in a lake, a corresponding volume of water is displaced, and forced out of the basin if the lake has an outlet. The sixth process is equally antagonistic to lakes, while the seventh has little influence on their permanence. Given time enough, these processes must bring the history of any lake to an end. The lowering of the outlet alone will accomplish this result if the bottom of the basin is above base-level. Many lakes have already become extinct, either through the filling or draining of their basins, or through both combined. It does not follow, however, that lakes will ever cease to exist, for the causes which produce them may be in operation contemporaneously with those which bring lakes now in existence to an end.

Lacustrine deposits. The beds of sediment deposited in lakes are similar in kind, in structure, and in disposition, to beds of sediment laid down in the sea; but river-borne sediment is more commonly concentrated into deltas, since waves and shore-currents are less effective in lakes than in the sea. Even the limestone made in the sea has its correlative in limestone made in some lakes. Some of it was made of the shells of fresh-water animals which thrived where the in-wash of terrigenous sediment was slight, some

of it from the calcareous secretions of plants,¹ and some of it was precipitated from solution.² While still soft, such deposits are called *marl*. Salt and iron-ore deposits are also sometimes made in lakes.

Extinct lakes. The former existence of lakes where none now exist may be known in various ways. If a lake basin was filled, its former area is a flat which bears evidence of its origin in its composition, its structure, and often in its fossils. Such a flat is commonly so situated topographically that the basin would be repro-

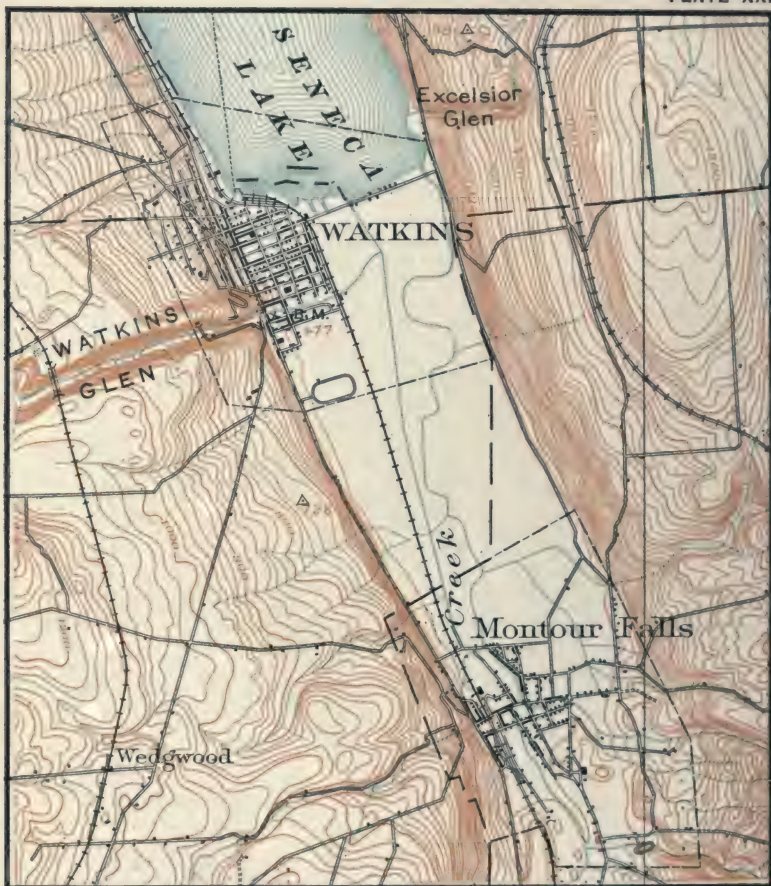


Fig. 269.— Shore terraces of Lake Bonneville, Wellsville, Utah. (Thompson and Holmes.)

duced if the lacustrine deposits were removed. To this general rule there are exceptions, as where a glacier formed one side of the basin when it was filled. If, on the other hand, the lake was destroyed by the lowering of its outlet, or by the removal of some barrier such as glacier ice, or by desiccation, shore phenomena, such as beaches, terraces (Fig. 269), spits, etc., may be found, even though there is no well developed flat corresponding to the bed of the lake. In time, such features are destroyed by subaërial erosion, so that they are most distinct soon after a lake becomes extinct.

¹ C. A. Davis, Jour. of Geol., Vol. VIII, pp. 485-497, and 498-503, and Vol. IX, pp. 491-506.

² Russell, Lake Lahontan, Mono. XI, U. S. Geol. Surv., Chap. V; also Third Ann. Rept., pp. 211-221. Gilbert, Lake Bonneville, Mono. I, U. S. Geol. Surv., p. 167.



The upper end of Seneca Lake, New York. The flat between Montour Falls and Watkins is a delta which has been built out into the lake by the in-flowing creek. Scale, about 1 mile per inch. (Watkins, N. Y., Sheet, U. S. Geol. Surv.)

Many lakes, some of them large¹ and many of them small, are known to have become extinct, while many others are now in their last stages, namely, marshes. Many others have been greatly reduced in size. Such reductions are often obvious where deltas are built into lakes. Thus the delta built by the Rhone into Lake Geneva is several miles in length, and has been lengthened nearly two miles since the time of the Roman occupation. The end of Seneca (N. Y.) Lake (Pl. XXI) has been crowded northward some



Fig. 270.— Terraces on the shore of the ancient Lake Lahontan, north of Pyramid Lake, Nevada. (Fairbanks.)

two miles by deposition at its head. Similar changes have taken place and are now in progress in many other lakes.

Salt lakes. A few lakes, especially in arid or semi-arid regions, are salt, and others are "bitter." Beside common salt, salt lakes usually contain magnesium chloride, and magnesium and calcium sulphates, as well as some other mineral substances. "Bitter" lakes usually contain sodium carbonate, as well as sodium chloride and sulphate, and sometimes borax. The degrees of saltiness and bitterness vary from freshness on the one hand to saturation on the other. The water of the Caspian Sea (lake) contains, on the

¹ Gilbert, Lake Bonneville, Mono. I, U. S. Geol. Surv.; Russell, Lake Lahontan, Mono. XI, U. S. Geol. Surv.; and Mono Lake, Eighth Ann. Rept., U. S. Geol. Surv., Pt. I; Upham, Lake Agassiz, Mono. XXV, U. S. Geol. Surv.; Salisbury and Kummel, Lake Passaic, Rept. of the State Geologist of N. J., 1893, and Jour. of Geol., Vol. III, pp. 533-560.

average, less salt than that of the sea; that of Great Salt Lake contains about 18%; that of the Dead Sea, about 24%; and that of Lake Van, in eastern Turkestan, the densest body of water known, about 33%.

Many salt lakes, such as the Dead Sea and Great Salt Lake, are descended from lakes which were fresh, while others, like the Caspian Sea, are probably isolated portions of the ocean. Lakes of the former class have usually become salt through a decrease in the humidity of the region where they occur. The water begins



Fig. 271.—Tufa domes, Pyramid Lake, Nevada. (Fairbanks.)

to be salty when the aridity is such that evaporation from the lake exceeds its inflow. The inflowing waters bring in small amounts of saline and alkaline matter, which is concentrated as evaporation takes place. The concentration may go on until saturation is reached, or until chemical reactions cause precipitation.

Deposits of salt and other mineral matters once in solution are making in some salt lakes at the present time, and considerable formations of the same sort have been so made in the past. Buried beneath sediments of other sorts, beds of common salt or of other precipitates are preserved for ages. Lime carbonate has been precipitated in quantity from some extinct lakes (Fig. 271).

Lakes which originate by the isolation of portions of the sea are salt at the outset. If inflow exceeds evaporation, they become

less and less salty, and may ultimately become fresh; otherwise they remain salt. If evaporation exceeds inflow they diminish in size and their waters become more and more salt or bitter.

Indirect effects of lakes. Lakes tend to modify the climate of the region where they occur, both by increasing its humidity and by decreasing its range of temperature. They act as reservoirs for surface-waters, and so tend to restrain floods and to promote regularity of stream flow. They purify the waters which enter them by allowing their sediments to settle, and so influence the work and the life of the waters below.

Origin of lake basins.¹ Lake basins arise in many ways, some of which have been pointed out on preceding pages. Most of them arise through processes of gradation. Some are formed by rivers (p. 185), some by waves and shore currents (p. 313), some by glacial erosion, some by glacial deposition (p. 268), and some by a combination of glacial erosion and glacial deposition. Others are formed by volcanic action, as when a lava flow dams a valley, or when a volcano leaves its cone with a depressed crater. Still others are formed by warpings of the earth's surface, and a few in other ways.

¹ Salisbury's *Physiography*, larger edition, p. 303.

CHAPTER IX

THE MOVEMENTS AND DEFORMATIONS OF THE EARTH'S BODY (DIASTROPHISM)

The outer parts of the lithosphere are subject to a variety of movements; some very rapid and some very slow, some very slight and some very great, some limited to small areas, some affecting extensive tracts, and some involving the whole earth-body. For practical treatment, they fall mainly into two groups, (1) the small and rapid, and (2) the great and slow. Sudden movements of local masses, such as avalanches and landslides, are put in the first class. Minute and slow movements, unless they rise to importance by long continuance, are here neglected.

MINUTE AND RAPID MOVEMENTS

The crust of the earth is in a state of perpetual tremor. For the most part, these tremors are too slight to be sensible, though detectable by delicate instruments. Some of them precede or follow sensible vibrations, such as earthquakes, but more of them have no connection with violent movements. Many spring from the ordinary incidents of the surface; waves, waterfalls, winds, tides, rainfall, the rise and fall of atmospheric pressure, the tread of animals, the rumble of traffic, the blasts of mines, and many other processes. These are serviceable for demonstrating the elastic nature of the crust, but are here neglected.

*Earthquakes*¹

When tremors of appreciable violence spring from sources within the earth, they are classed as *earthquakes*. The causes are various;

¹ Recent and instructive books on Earthquakes are Dutton's *Earthquakes*; Hobbs's *Earthquakes*; *An Introduction to Seismic Geology*; Milne's *Earthquakes* (4th ed.), and the same author's *Seismology*; and Knott's *Physics of Earthquake Phenomena*.

the most prevalent is probably the fracture of rocks and the slipping of strata on each other in the process of faulting. To the same class belong movements due to slumping, which is, in reality, superficial faulting. Tremors often attend volcanic eruptions. Such tremors are attributable to the sudden fracture and displacement of rock by the movements of lava, or by the expansion due to rapid and unequal heating. They are often attributed to the sudden

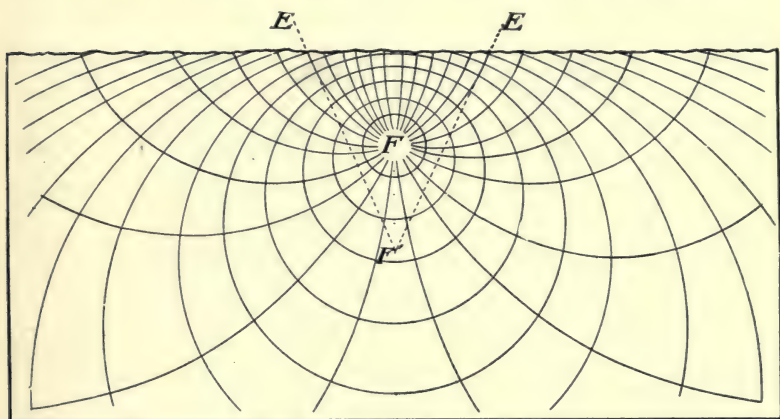


Fig. 272.—Diagram illustrating by closed curves the different rates of propagation of seismic tremors from a focus F , and, by lines normal to these, the changing directions of propagation of the wave-front. It will be seen that the paths of propagation curve upwards in approaching the surface. If the lines of emergence, as at E and E' , be projected backwards, as to F' , the points of crossing will be below the true focus.

generation or cooling of steam in underground conduits, crevices, and caverns. Earthquake vibrations also spring from the collapse of the roofs of subterranean caverns.

Points of origin;—foci. It is probable that nearly all earthquake movements start at depths of less than ten miles, and most of them at depths of less than five. The earlier estimates which placed some of the foci deeper, seem to be defective. The depth of the sources of disturbance is usually estimated by noting the directions in which bodies are thrust during an earthquake, plotting these directions, and projecting them backwards to their underground crossings (lines EF' , Fig. 272). This only gives a

rude first approximation to the location of the focus (point, line, or plane), and all estimates made in this way are subject to important corrections.¹

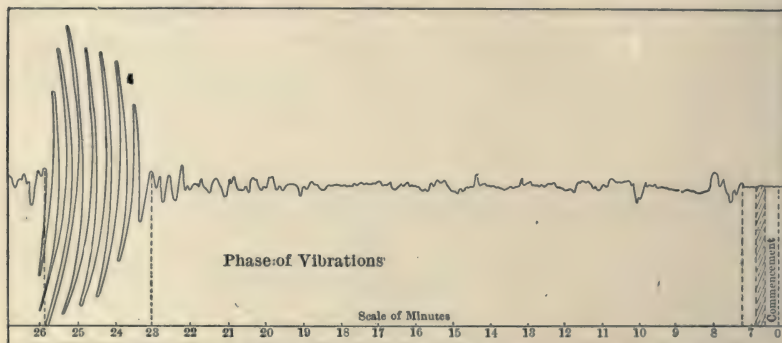


Fig. 273.— Seismograph of earthquake in Punjab, India, April 4, 1905, showing the actual amount of movement. (Montessus de Ballore.)

The amplitude of the vibrations. From the disastrous effects of earthquakes it might be inferred that the vibrations have large amplitudes; but it is chiefly their suddenness that makes them



Fig. 274.— A fissure on East Street, San Francisco, near the water front, in "made ground." (Lindgren, U. S. Geol. Surv.)

¹These corrections are due to the decrease in the elasticity, temperature, density, and continuity of the rock as the surface is approached. See the authors' larger work, Vol. I, p. 528 et seq.

effective. Except at their points of origin, they are usually only a fraction of a millimeter in amplitude, and seldom exceed a few millimeters. A sudden shock with an amplitude of 5 or 6 millimeters is sufficient to shatter a chimney. It is the oscillation of the rock particles transmitting the vibrations that is here meant, not the movement of objects on the surface, which is often much greater. Just as a marble lying on a floor may be made to bound



Fig. 275.— Track of electric railway, between South San Francisco and San Bruno Point. (Photo. by Moran.)

several inches by a slight tap of a hammer some distance away, so a sufficiently sudden rise of the earth-surface for a fraction of an inch only, may project loose bodies many feet.

Destructive effects. The disastrous effects of earthquake shocks result from (1) the suddenness and strength of rather minute vibrations of earth-matter, and from (2) the freedom of motion of the bodies affected. The deeper rocks, where sensibly continuous, transmit seismic vibrations without appreciable disruptive effect so far as known (though the origin of crevices has been assigned to this cause); but bodies at the surface are fractured, overturned, and notably displaced. The tap of a hammer sends an almost imperceptible vibration along the floor, but this vibration throws well into the air the glass ball beneath which it runs. Similarly the minute seismic vibrations travel miles from their origin through continuous substance with little result, and yet may then hurl a loose or unstable body to destruction. Earthquake waves striking

the sea-border may thrust the waters off shore, and the return wave may overwhelm the coast (Fig. 276). Sea-waves doubtless arise also from a sudden stroke of seismic vibrations on the sea-bottom.

Direction of throw. Immediately above the point, line, or plane of origin (*epicentrum* or *epi-focal point, line, or plane*), bodies are projected upwards. Elsewhere at the surface plane, the thrust is oblique. The destructiveness commonly increases for a certain



Fig. 276.— Great sea-wave on the coast of Ceylon. (Sieberg.)

distance from the epi-focal point, line, or plane, and then diminishes. Lines drawn through points of equal effect (*isoseismals*, Fig. 277) are not usually circles or regular ellipses, and their departures from these forms represent differences of elasticity, etc. As most earthquakes originate from lines, planes, or masses, rather than points, there are differences in the intensity of vibration at different points on the lines or planes of origin, and these differences introduce inequalities in propagation and in surface effects.

Rate of propagation. The progress of a seismic wave varies appreciably. The violent vibrations on the surface near the place

of origin are the most irregular, and the stronger vibrations generally have greater speed than the weaker ones. The vibrations

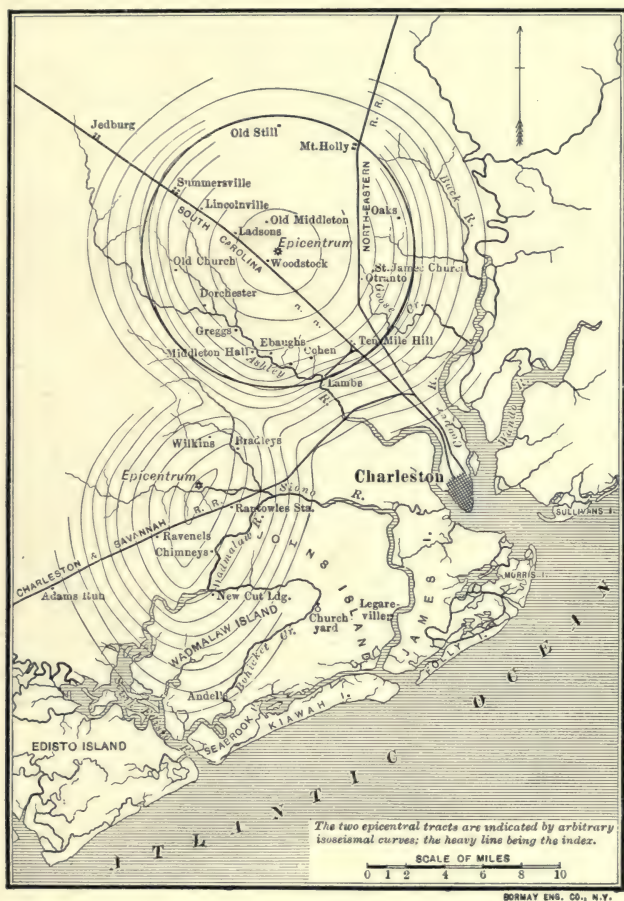


Fig. 277.—Epicentral tracts of the Charleston earthquake, with isoseismal lines. (Dutton, U. S. Geol. Surv.)

propagated to great distances through and around the earth are more uniform in rate, being about 1.85 miles (3 km.) per second for those which follow the surface, about 5.7 miles (9.17 km.) per second for the speedier set that goes through the earth, and

about 3.9 miles (6.25 km.) for the second set that goes through the earth.¹

Distribution of earthquakes. Over large portions of the globe, severe earthquakes are rare, but in certain regions they are, unfortunately, frequent. In general, earthquakes are likely to be rather frequent where geologic changes are in rapid progress, as along belts of young mountains where the stresses are not yet adjusted, or at the mouths of great streams where deltas are accu-

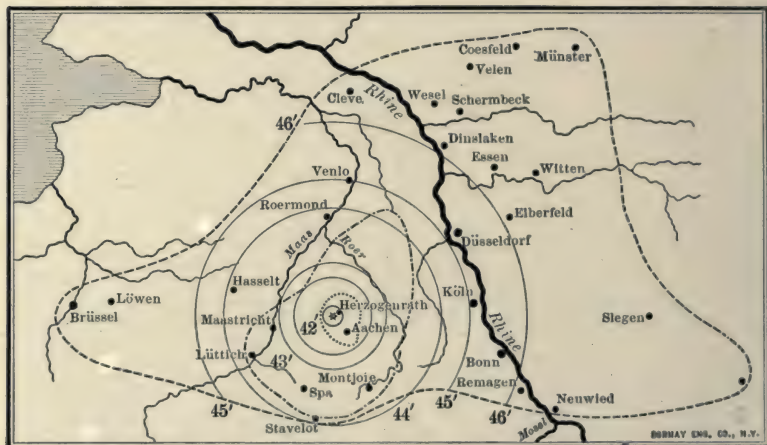


Fig. 278.—Coseismal lines for each minute, Herzogenrath (Germany), earthquake of October 22, 1873. (Lasaulx.)

mulating, or about volcanoes where temperatures and strains are changing, or on the great slopes, particularly the submarine slopes, where adjustments to inequalities of stress are in progress. Not a few, however, occur where the special occasion is not obvious.

The Geologic Effects of Earthquakes

Geologically, earthquakes are of less importance than many gentler movements and activities. Disastrous as they sometimes are to human affairs, they leave few distinct marks which are more than temporary. During the passage of notable earthquake

¹ The Physics of Earthquake Phenomena, C. G. Knott, 1908, p. 226.

waves the solid rock is probably often fractured, though the fractures are rarely observable at the surface where it is covered by deep soil. Elsewhere the crevices are readily seen, especially if they gape. In a few instances, surface-rock has been seen to be thoroughly shat-



Fig. 279.— Map showing in black the principal earthquake regions of the Old World. (Montessus de Ballore.)

tered after the passage of an earthquake, as in the Concepcion earthquake of 1835.¹ Joints which were closed before, are often opened during an earthquake. Thus in northern Arizona, not far from Canyon Diablo, there is a crevice traceable for a con-

¹ Darwin, *Journal of Researches*, 1845, p. 303.

siderable distance which is said to have been opened during an earthquake (Fig. 281). Locally, it gapes several feet. During an earthquake which shook the South Island of New Zealand in 1848, "a fissure was formed averaging 18 inches in width, and traceable



Fig. 280.— Map showing the principal earthquake regions of the New World. (Montessus de Ballore.)

for a distance of 60 miles, parallel to the axis of the adjacent mountain chain.”¹ The development of fractures or the opening of joints is sometimes accompanied by faulting. This was the case in Japan during the earthquakes of October 28, 1891, when the

¹ Geikie, Text-book of Geology, 4th ed., p. 372.

surface on one side of a fissure, which could be traced for 40 miles, sank 2 to 20 feet (Fig. 282). In this case there was also notable



Fig. 281.— Fissure produced by earthquake. Arizona.

horizontal displacement, the east wall of the fissure being thrust locally as much as 13 feet to the north.¹



Fig. 282.— Fault in Japan, 1891. (Koto.)

¹ Koto, Jour. Coll. Sci., Japan, Vol. V, Pt. IV (1893), pp. 329, 339. Cited by Geikie, loc. cit., p. 373.

Changes of surface. Circular surface openings or basins are sometimes developed during earthquakes. This was the case during the Charleston earthquake of 1886,¹ and similar effects have been noted elsewhere. These openings often serve as avenues of escape for ground-water, gases, and vapor. They are commonly supposed to be the result of the collapse of caverns, of other subterranean openings, or the compacting of rock, the collapse often causing the forcible ejection of water. Such openings are likely

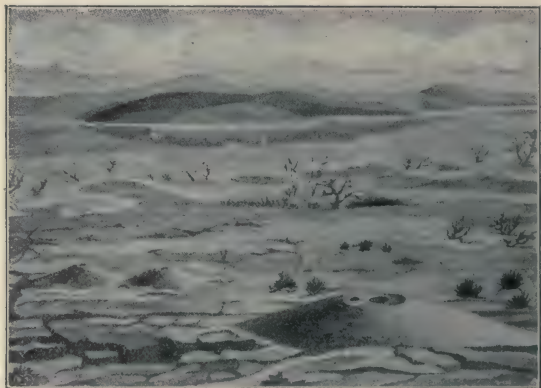


Fig. 283.—Sand cones and craterlets observed after the earthquake of 1861, in Greece. (Schmidt.)

to be formed only where the surface material is incoherent. Sand cones and craterlets are sometimes developed (Fig. 283). During the California earthquake of 1906, the ground was much broken along the line of the fault which caused the shock (Fig. 284). Earthquakes sometimes dislodge masses of rock in unstable positions, as on slopes or cliffs, and occasion slumps and landslides.

Effects on drainage. The fracturing of the rock may interfere with the movement of ground-water. After new cracks are developed or old ones opened or closed, the movement of ground-water adapts itself to the new conditions. It follows that springs sometimes cease to flow after an earthquake, while new ones break out where there had been none before. The character of the water

¹ Dutton, Ninth Ann. Rept., U. S. Geol. Surv., pp. 209-528.

of springs is sometimes changed, presumably because it comes from different sources after the earthquake. Joints may be so widened as to intercept rivulets. Where faults accompany earthquakes, they may occasion ponds or falls where they cross streams.¹

Effects on standing water. Some of the most destructive effects of earthquakes are felt along shores. The great sea-waves of the Lisbon earthquake (1755) and of the earthquake on the coast of



Fig. 284.—Characteristic surface appearance of the fault line, south end of Tomales Bay. (Photo. by Newsom.)

Ecuador and Peru in 1868, were most destructive. Such waves have been known to advance on the land as walls of water 60 feet in height. They are most destructive on low coasts where the water may sweep over great areas of land. The great loss of life during an earthquake is often caused by such waves. Lakes are also affected by earthquakes, but their waves are much feebler than those of the sea, and are not often very destructive.

Earthquake shocks are sometimes remarkably destructive to the life of lakes and seas. Thus during the Indian earthquake of

¹ Oldham, Report on the Indian Earthquake of June 12, 1897, p. 138. Mem. Geol. Surv. of India. Cited by Geikie, loc. cit., p. 374.

1897, "fishes were killed in myriads as by the explosion of a dynamite cartridge. . . . and for days after the earthquake the river (Sumesari) was choked with thousands of dead fish. . . . and two floating carcasses of Gangetic dolphins were seen which

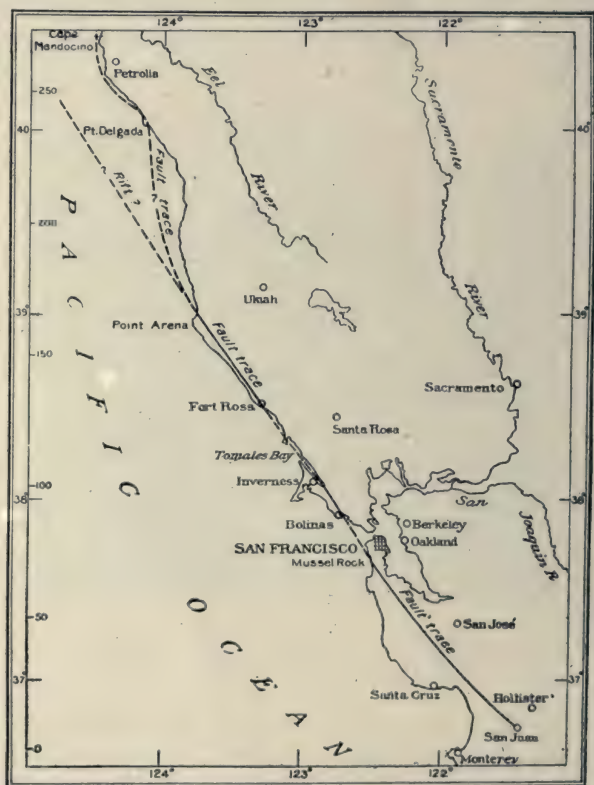


Fig. 285.—Line of the California fault. (U. S. Geol. Surv.)

had been killed by the shock.”¹ This wholesale destruction of life is of interest since the surfaces of layers of rock, often of great age, are sometimes covered with fossils in such numbers as to indicate that the animals were killed suddenly and in great numbers, and their bodies quickly buried. It has been suggested that such

¹ Oldham, loc. cit., p. 80.

rock surfaces may perhaps be memorials of ancient earthquake shocks:¹

Changes of level. Permanent changes of level sometimes accompany an earthquake. Thus after the earthquake of 1822 "the coast of Chili for a long distance was said to have risen 3 or 4 feet."² Similar results have occurred on the same coast at other times, and on other coasts at various times. Depression of the surface is perhaps even more common than elevation. Thus on the coast of India all except the higher parts of an area 60 square miles in extent were sunk below the sea during an earthquake in 1762. Widespread depression in the vicinity of the Mississippi in Missouri, Arkansas, Kentucky, and Tennessee accompanied the earthquakes of 1811 and 1812. Some of the depressed areas were converted into marshes, while others became the sites of permanent lakes. Reelfoot Lake, mainly in Tennessee, is an example. Change of level is often involved in faulting, and faulting is probably rather common in connection with earthquakes.

Changes of level are not confined to the land. Where earthquake disturbances affect the sea-bottom in regions of telegraph cables, the cables are often broken. In such cases notable changes have sometimes been discovered and recorded when the cables were repaired. In one instance (1873) the repairing vessel off the coast of Greece³ found about 2,000 feet of water where about 1,400 feet existed when the cable was laid. In another instance (1878) the bottom was so "irregular and uneven for a distance of about two miles, that a detour was made and the cable lengthened by five or six miles." In still another case (1885) the repairing vessel found a "difference of 1,500 feet between the bow and stern soundings." These records point to sea-bottom faulting on a large scale.

SECULAR MOVEMENTS

The minute and momentary oscillations of earthquakes are very unlike the slow movements of continents or ocean basins, or even

¹ Geikie, *Text-book of Geology*, 4th ed., p. 375.

² *Ibid.*, p. 376.

³ Forster, *Seismology*, 1877. Summarized in *Am. Geol.*, Vol. III, 1889, p. 182.

the slow wrinkling of mountain folds. Rivers may wear down their channels across a mountain range as fast as it rises athwart them, and the movements of continents are even slower; but far apart as these contrasted movements are, they are doubtless associated in cause; and the earthquake shock is often merely an incident in the formation of a mountain range or in the movement of a continent.

The great movements may be classed (1) as continent-making (2) plateau-forming and (3) mountain-folding; or as (1) general (epeirogenic) or (2) as concentrated (orogenic); as (1) vertical and (2) horizontal, and dynamically, as (1) thrust and (2) stretching movements. These distinctions are analytical conveniences but are not exclusive of one another, for continental movements often involve mountain-making, vertical movements usually involve horizontal movements, and stretching usually attends the outer bends of thrust folds.

Present movements. Observations on seacoasts show that some shores are slowly rising and some slowly sinking, *relative to the ocean-level*. It is not certain what these movements are *relative to the center of the earth*. All parts of the coast may be sinking, some faster than others, while the ocean-surface goes down at an intermediate rate; or, theoretically, all parts may be rising, but at different rates. Some lands may be actually rising relative to the center of the earth, and others sinking, while the ocean-level has an intermediate movement or none at all. We are accustomed to take the sea-level as a standard, as though it were stationary, which is probably not the fact. A general shrinkage of the earth is probably going on, carrying down the surface of both land and sea. It is possible that the shrinkage is so great that upward warpings and foldings do not usually equal it, and hence nearly all movement may be really toward the earth's center. This seems to be implied by the crumpling of the surface. The popular disposition is to regard earth movements generally as "upheavals." There is also a predilection for regarding the rigid land as moving, and the mobile sea-level as fixed. In reality, the sea is an extremely adaptive body which settles freely into the irregular hollows of the lithosphere and is shifted with every warping of the

latter. Whatever change affects the capacity of the abyssal basins affects the sea-level. If the basins are increased, the sea settles deeper into them; if they are decreased, the sea spreads out more widely on their borders. The one thing that gives a measure of stability to the sea-level is the fact that all the great basins are connected, and so an *average* is maintained. For this reason the sea-level is the most convenient basis of reference, and has become the accepted datum-plane, notwithstanding its instability and its complete subordination to the lithosphere. If there were some available mode of measuring the distance of surface points from the center of the earth, it would give absolute data and would reveal much that is now uncertain respecting the real movements of the surface.

The classes of movements. The existence of land depends on protuberances on the surface of the lithosphere. If the lithosphere were perfectly spheroidal, water would cover it everywhere to a depth of nearly two miles. *To maintain the existence of land the protuberances must be renewed from time to time;* otherwise the land would in time be degraded to the lowest depths of wave action. The renewal has been brought about again and again in geologic history by movements that have restored the protuberances. With every such movement, the oceans seem to have withdrawn more completely within the basins, while the continents have stood forth more prominently until again worn down. This renewal of protuberances appears to have been *periodic in its great features*, with long intervals between. In these intervals, the land was worn down by rivers, waves, etc., and the sea crept out upon the lower parts of the continents, forming continental shelves. Before complete submergence was effected, however, renewed deformations checked the progress of submergence and rejuvenated the continents.

Beside the great movements, numerous minor warpings or oscillations of the surface have been in almost constant progress. Some of these are probably only incidental features of the larger movements made necessary to complete the adjustment to the smaller stresses left after the great stresses are relieved, but others are probably due to local and special causes of the lesser sort.

Minor Movements

Gentle movements seem to have affected nearly every portion of the surface of the lithosphere at nearly all stages of its history. They have often had much to do with the particular places and forms of deposits. Slow relative sinkings of sea-borders have permitted deposition to go on in shallow water for long periods without building the bottom up into land, and slow relative swellings of land tracts have permitted the agents of erosion to get sediments for such deposits. Such movements have also shifted the borders of lands and seas, and with them, the areas of erosion and deposition. These movements may have amounted to a few inches, a few feet, or a few fathoms per century. They are sometimes reciprocal, one area being bowed up while another near by is bowed down. How far these are merely local or regional, due to loading, unloading, changes of temperature, and other local causes, and how far they are the milder phases of the great body movements of the earth or the incidental creep arising from these, it is difficult to decide.

The Great Periodic Movements

1. Mountain-folding. Along certain tracts, the shell of the earth has been folded into wrinkles, thus forming folded mountains. The shell so folded, judged from the nature of the folds, seems to be quite superficial, reaching only a few miles in depth. Sometimes the strata were very closely folded, and even intensely crumpled. The forces that caused the folding took the form of lateral thrusts. The folds themselves were usually lifted, showing that there was an upward component to the horizontal thrust, but the latter was the dominant factor. The folds were crumpled *outward* rather than *inward*, which implies that there was crowding below, rather than shrinkage. The folds are sometimes nearly upright and symmetrical, and sometimes inclined and asymmetrical, as illustrated in Chapter XI. When the folds lean, it is commonly inferred that the active thrust was from the side of the gentler slope, and pushed the fold over toward the resisting side, but this is not always a safe inference, for the original attitude of the beds has much to do with the way they yield. Systems of

folded mountains usually embrace a series of roughly parallel folds, the whole forming an anticlinorium (Fig. 286).

Distribution of folded mountain systems. The location of folded mountains is so often near the borders of the continents that the relation is probably significant, but there are very notable excep-

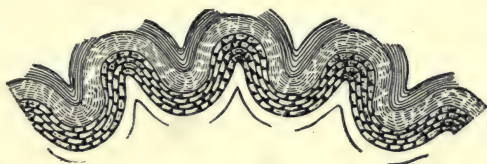


Fig. 286.—Anticlinorium: diagrammatic. (Van Hise, U. S. Geol. Surv.)

tions. Among these are the Urals, the complex series that stretches from the Pyrenees to the Hindu Kush, the Central Asian chain which embraces the Sayan, the Altai, and the Tien Shan, and many minor ranges.

Folding movements had extraordinary prevalence in the early ages. The Archean rocks are almost universally crumpled, often in the most intricate fashion, and the proterozoic formations are much folded. After the inauguration of the well-known sedi-

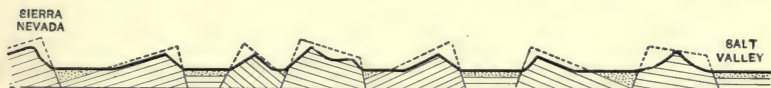


Fig. 287.—Ranges of the Great Basin. Length of section, 120 miles. (Gilbert.)

mentary eras, folding appears to have taken place chiefly at long intervals, and for any given period to have been concentrated along certain tracts. The Appalachians and the Juras are types.

2. Plateau-forming movements. An important phase of massive movement was the relative settling or raising of great blocks or segments as though by vertical rather than horizontal forces. The great plateaus are examples of the protrusive phase of this action; perhaps the great "deeps" of the ocean bottom, and some of the basins or troughs (*Graben*) on the continents, are examples of the depressional phase. The plateaus usually embrace numerous

blocks which were moved in different degrees, and were often tilted individually (Fig. 287). At the surface, these blocks are separated by fault-planes, but below, some of the faults pass into flexures. Most such flexures are monoclinical. Plateau-forming movements are to be compared with the continent-forming movements, rather than with mountain-foldings, differing from the former chiefly in magnitude. Plateaus may be regarded as parts of a continental mass that have suffered special additional movement. Plateaus stand in some such relation to continents, as one fault block of a plateau does to the whole plateau. They are probably to be regarded as the results of body deformations, while the mountains are the result of the folding of the shell, affecting only a few miles of the outside.

3. Continent-forming movements. These are widespread movements affecting large masses of the body of the earth, if not its whole outer portion. Two or more continents are often affected by similar movements at the same time, and it is the view of many geologists that all continents are usually affected simultaneously by movements of a like kind, resulting in emergence or submergence, while the ocean basins are affected by movements of the opposite phase. These are thus thought to be body movements. The depression of the basins and the relative elevation of the continents are regarded as reciprocal parts of a world-wide adjustment. While well supported both by observation and theory, this view cannot be said to be universally accepted. Movements of this class seem to have started early in the history of the globe, and to have been renewed from time to time, rejuvenating the continents and developing the basins. Under the view that the earth is essentially solid throughout, these movements are regarded as deep-seated deformations, while the mountain folding is regarded as but the wrinkling of the earth's skin to fit its changed body.

Downward movements are regarded as the primary ones, and horizontal movements as a necessary result of them. The primary cause is believed to be an increase of the density of the earth, actuated by gravity and the molecular and sub-molecular attractions. The master movement is thought to be the sinking of the great basins, whose specific gravity is greater than that of the con-

tinents. The reasons for this will be set forth later. If the ocean basins and the continental platforms, respectively, be regarded as the surfaces of great segments of the earth all of which are crowding toward the center, the stronger and heavier segments may be conceived to take precedence, squeezing the weaker and lighter ones between them. The consequent swelling up of the lighter segments accounts for the relative protrusion of the continents.

The area of the more depressed segments is almost exactly twice that of the protruding ones, if we count the 10,000,000 square miles now covered with shallow water as parts of the continental platforms. Roughly approximated in millions of square miles, the major depressed segments are as follows: The Pacific 60, the Indian 27, the South Atlantic 24, the North Atlantic 14, leaving 8 for minor depressions. The elevated segments are the Eurasian 24, the African 12, the North American 10, and the South American 9, leaving 10 for the minor blocks.

The downward movement of the master segments and the crowding of the smaller and lighter segments between them involves deformations of the latter. Those that spring from the deeper, more massive crowdings affect the continental platforms generally, or at least broadly, while the crowding of the more superficial parts affects the continents more locally. The great plateaus lie chiefly at angles in the great segmental movements, where special crowding naturally arises. It is obvious that on the borders of the continental segments there would be special bowings, and this tallies with the archings common on border tracts, even when no folding takes place. The shell of the earth is free at the surface, and as a result, folding and faulting are the modes of easiest accommodation, while in the deeper parts which are under great pressure, the mass must be deformed throughout.

The periodicity of the movements is assigned to the rigidity of the thick, massive segments which must be deformed to accomplish a readjustment. Because of this rigidity, stresses may accumulate for a period until they come to equal the resistance opposing them, after which a further increase of the stresses brings on a yielding and forces a readjustment. When masses, under stress, once begin to yield in the direction of the free surfaces, their attitudes

for resistance become less favorable, and hence the stress compels continued yielding until it is fully eased. After this a period is required for stress to accumulate, sufficient to produce another general deformation. Meantime the minor stresses that may remain, or may be produced by the great deformations, tend to ease themselves and thus give rise to the minor movements (p. 354). Other minor movements are doubtless due to local causes.

The extent of the movements. Between the highest elevation of the land and the lowest depth of the ocean, there is a vertical range of nearly twelve miles. From the Tibetan plateau, where a considerable area exceeds three miles in height, to the Tuscarora deep, where a notable tract exceeds five miles in depth, the range is eight miles. This may fairly represent the vertical range of differential movement of large areas. The average height of the continents is about three miles above the average depth of the oceans, and this may be taken as the differential movement of the great segments.

If the protruding portions of the lithosphere were graded down and the basins graded up to a common level, this level would lie about 9,000 feet below the surface of the ocean. Referred to this datum plane, the continents, with an area about half that of the ocean depths, have been squeezed up *relatively* about two miles, and the basins have sunk about one mile. The *total downward movement*, representing the total increase of density of the earth, is quite unknown, but from theoretical considerations, it would appear to be far greater than the differential movement, which means that all segments have probably moved toward the center, the basin segments about three miles more than the continental.

The extent of the *lateral movements* of the shell has a peculiar interest, for it bears, theoretically, on the downward movements. Every mile of descent of the crust represents more than 6 miles ($6.28 = 2\pi$) shortening of the circumference. If the vertical movements were limited to the *relative* ones just named, the mile of descent of the ocean basins would give but little more than 6 miles excess of circumference for the lateral thrust and crumpling of the shell. How far does this go in explaining mountain folds? The shortening represented by the folds of the Alps has been estimated

at 74 miles;¹ the shortening for the Appalachians in Pennsylvania, not including the crystalline belt on the east, at 46 miles;² that of the Laramide Range in British America at 25 miles,³ and that of the Coast Range in California at 9 to 12 miles.⁴

Though these estimates cannot be taken as measurements, they are sufficiently close approximations to make it clear that the amount of shortening of the shell involved in mountain folding is large. These estimates represent only that shortening of the circumference effected at certain times and places; the whole shortening of a circumference involves the shortening implied by all the transverse folds on a given great circle. Usually a great circle does not cross more than one or two strongly folded tracts of the same age, from which it is inferred that the shortening on each great circle at any one time was largely concentrated in a few tracts running at large angles to each other. If the folding of one of the main mountain ranges be doubled, it may perhaps represent roughly the shortening for the circle normal to it, *for its own period of folding*. If one is disposed to minimize the amount of folding, the estimate of the shortening may perhaps be put roundly at 50 miles on a circumference, for each of the great mountain-making periods; or, if disposed to make the estimate large, the shortening may be put at 100 miles, or even more. For the whole shortening since the beginning of the Paleozoic, perhaps twice these amounts might suffice, for while there have been several mountain-making periods, perhaps no more than two or three are entitled to be put in the first order. Assuming the circumferential shortening to have been 50 miles during a given great mountain-folding period, the appropriate radial shortening is 8 miles. For the more generous estimate of 100 miles, it is 16 miles. If these estimates are doubled for the whole of the Paleozoic and later eras, the radial shortening is 16 and 32 miles, respectively. The shortening for earlier eras can hardly be estimated from present data.

¹ Heim, *Mechanismus der Gebirgsbildung*, p. 213.

² Claypole, *Am. Nat.*, Vol. XIX, p. 257, 1885.

³ McConnel, *Geol. Surv. of Canada*, p. 33 D, 1886.

⁴ LeConte, *Elements of Geology*, 5th ed., p. 266.

Causes of Secular Movements

The volume of the earth depends on two sets of forces, acting in opposition to one another, (1) *the concentrating forces*, consisting of (a) gravity and (b) molecular and sub-molecular attractions, and (2) *the forces which resist concentration*, consisting of (a) heat and (b) molecular and sub-molecular resistances.

1. **The centripetal forces.** The best known of the concentrating forces is gravity, which tends to bring all parts of the earth as near the center as possible, the heavier beneath the lighter.¹ The gravitative force of the earth causes a pressure of about 3,000,000 atmospheres at its center, and a graded series of lesser pressures from the center to the surface. This is a constantly acting force and tends to bring about greater density whenever any molecular movement permits it.

In addition to gravity, there are attractive agencies acting between molecules, atoms, ions, and electrons, which co-operate with gravity in accordance with laws of their own. Their general effect is to give matter denser forms. How far these may go by united and prolonged action is not determined, but there is ground for believing that the density of the interior may still be increased by such action. It is known that substances which crystallize in a given way under surface pressures may be re-aggregated into denser forms under higher pressures. It is a general law that re-aggregation under pressure takes the densest form available. Re-aggregation in the interior thus probably means increased density, and it may be constantly going on. It has even been suggested that complex molecules may be organized under such conditions as obtain in the earth's interior, but for the present this must be regarded as merely speculative.

While we must hold final judgment in suspension until fuller knowledge of the laws of molecular, atomic, and sub-atomic combination under extremely high pressures and temperatures is developed, it is permissible even now to entertain the view that gravitational, molecular, atomic, and sub-atomic agencies have been and are still at work tending to increase internal density.

¹ For distinctions between gravitational *energy* and gravitational *force* see the authors' larger work, Vol. II, pp. 552-553.

2. The resisting agencies. The condensing agencies are more or less held in check by resisting agencies. Heat is the most familiar of these. It is abetted by molecular and atomic arrangements, and by factors in the ultimate structure of matter, not as yet understood. It has been usual to regard the primitive state of the earth as one of intense heat, and to assign its subsequent reduction of volume almost solely to loss of heat. This is not the view here favored. On the contrary, the heat is supposed to have been chiefly developed by forceful reduction of volume. The heat thus developed is one of the forces which check the further decrease of volume. Loss of heat is a cause of shrinkage, but its effect is thought to be less than that of molecular, atomic, and sub-atomic rearrangements of the material of the earth.

The Original Distribution of Heat

Very different views as to the original state of the matter of the earth are entertained according as the older or the later hypotheses of the origin of the earth are followed. These will be set forth in Chapter XII.¹ In the hypotheses which assign to the young earth a molten state, the original temperature is usually held to have been high, and its distribution somewhat uniform throughout the interior. Cooling afterward affected only a moderate depth, usually computed to be little more than 200 miles. Under the planetesimal hypothesis, which is here favored, the theoretical distribution of the internal heat arising from compression is shown in Fig. 288. The nature of this distribution is such that heat would be conducted from the deep interior to the outer zone 800 to 1,200 miles thick, faster than from the latter onward, with the result of raising the temperature of the outer zone while that of the deep interior falls. The result of this should be a severe crowding of the outer zone upon itself, in shrinking to fit the deep interior as it loses heat and shrinks. This crowding of the thick outer zone upon itself is the assigned cause of the great deformations that gave rise to the abysmal basins and the continental platforms.

Very important discoveries have recently been made relative

¹ They may be found more fully stated in the authors' larger work, Vol. I, pp. 559-574 and Vol. II, pp. 1-81.

to the effects of radioactivity springing from the spontaneous decomposition of uranium, thorium, and some other substances, on the temperature of the earth. The heat thus generated is even held to be sufficient to account for the heat that is lost from the earth's surface, and for the rise of temperature below the surface.

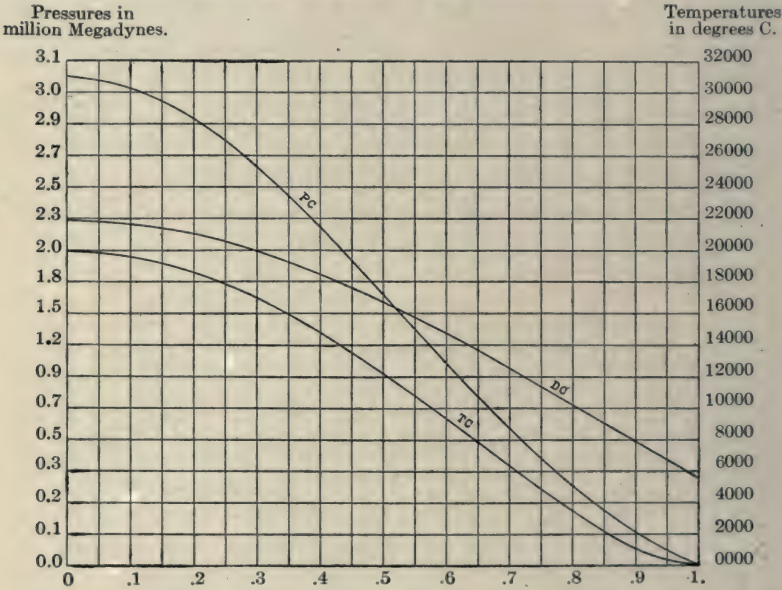


Fig. 288.— Diagram illustrating the distribution of temperature in the interior of the earth under the accretion hypothesis (neglecting the heat from infall and other external sources). The divisions of the base-line represent fractions of the earth's radius. The vertical divisions represent both pressure in megadynes per sq. cm., nearly the same as atmospheres per sq. in., at the left, and temperatures in degrees C. at the right. The upper curve at the left, PC, is the pressure curve. The middle curve, DC, is the density curve, beginning at 2.8 at the surface and reaching nearly 11 at the center. The lower curve, TC, is the temperature curve, rising from the surface temperature, 0° C., at the right, to 20,000° C. at the center. It is to be noted that the portion of this curve at the left, representing the deeper part of the earth, is convex upwards, while the portion at the right is concave. It will be seen that the gradient increases from the center to a point between .6 and .7 radius, and then decreases, and that between .8 radius and the surface, a distance of about 800 miles, the decrease is notable. This means that with an equal co-efficient of conductivity, the flow from the center outward to .6 or .7 radius will be faster than the flow from .8 to the surface, neglecting the immediate surface effects of cooling. In other words, the heat will be increasing between .8 and 1. Curves worked out by Dr. Lunn.

If the effect of radioactivity be superposed on that of compression, it modifies the curve of Fig. 288, by raising its outer part, making it accord with the observed temperatures shown in deep excavations.

Observed temperatures in deep excavations. As the earth is penetrated below the zone of seasonal changes, by wells, mines, tunnels, and other excavations, the temperature is almost invariably found to rise. The rate of rise, however, is far from uniform. If we set aside as exceptional the unusually rapid rise near volcanoes and in other localities of obvious igneous influence, the highest rates are more than six times the lowest, the range being from 1° F. in 20 feet, to 1° in 130 feet, with an average of 1° in 50 to 60 feet. The more recent deep borings in which the temperatures have been carefully recorded indicate a slower rate of rise, say 1° for 80 feet. It is not probable that the average rates of increase as determined by observation continue to the center of the earth. One degree in 60 feet, continued to the earth's center would give a temperature of $348,000^{\circ}$ Fahr., and 1° Fahr. in 100 feet would give $209,000^{\circ}$ Fahr. It is much more probable that the rate of rise diminishes below the superficial zone, and that the temperatures cited are far in excess of those actually existing at the center.

The amount of loss of heat. The amount of loss of interior heat may be estimated by that which is observed to be passing outward through the rock, or by computing the amount which should be conveyed outwards with the estimated temperature gradients, and with the known conductivity of rock. On this basis estimates of the loss of heat in 100,000,000 years range from 10° C. (18° Fahr.) (Tait¹) to 45° C. (81° Fahr.²), for the whole earth. This is an exceedingly small result, and emphasizes the low conductivity of rock.

The amount of shrinkage from loss of heat. With this amount of cooling, the shrinkage from this cause may be calculated, the average coefficient of expansion of rock being known. This has been done, both experimentally and theoretically. For a loss of 10° C. of heat, the circumferential contraction is calculated to be 1.6 to 2.35 miles; for a loss of 45° C., 7.27 to 10.5 miles. These results

¹ Tait, Heat, p. 225.

² Daniell's Physics, p. 407.

are so small that unless there is a serious error in the estimated rate of thermal loss, or in the coefficients of expansion, cooling would seem to be *a very inadequate cause for the shrinkage implied by mountain folds, overthrust faults, and other crustal deformations*. This inadequacy has been strongly urged by various students of the problem.¹ In view of the apparent incompetency of external loss of heat, the possibilities of distortion from other causes deserve consideration.

The transfer of internal heat. Under certain possible conditions, more heat would flow from the central parts of the earth to outer zones than would be passed through them to space, as already stated (Fig. 288). As a result, the temperature of the central parts might be falling while that of sub-surface zones was rising. A lowering of the average temperature of the inner half of the earth 500° C. and a raising of the temperature of the outer half an equal amount, would cause a lateral thrust of about 83 miles. Some transfer of this kind is among the theoretical possibilities under the planetesimal hypothesis. The process could not continue indefinitely; but computations imply that it may still be in progress.

The rise of lavas. If lavas are forced out from beneath the surface, a compensating sinking of the outer shell will follow. The great lava-flow of the Deccan is credited with an area of 200,000 square miles, and a thickness of 4,000 to 6,000 feet. Vast as this is for a lava-flow, it would form a layer only about 5 feet thick if spread over the whole surface of the globe. The compensatory sinking would cause a lateral thrust, on any great circle, of about 31 feet only. It requires a very generous estimate of the lavas poured out between any two great mountain-making periods since the beginning of well-known geological history, to cause a horizontal thrust of any appreciable part of that involved in the folding of a typical mountain system. The case is different, however, if we go back to the Archean times when the amount of extrusion was very large. Very notable distortion may have arisen from the extravasation of the lavas of that era.

Intrusions of lava rising from lower to higher levels in the

¹ Fisher, *Physics of the Earth's Crust*, Chap. VIII; and Dutton, *Penn. Monthly*, Philadelphia, May, 1876.

earth would have a dynamic effect similar to that of extrusions, so far as the outer portion of the earth is concerned, and the amount of intrusive rock is probably greater than the amount of extrusive;—far greater if the views of vulcanism here entertained are correct.

Rotational possibilities. The oblateness of the present earth is accommodated to its present rate of rotation. It is assumed that such accommodation has always obtained, and that if the rotation has changed, the form of the earth has changed also. The more oblate the spheroid, the larger its surface shell and the less the total force of gravity. If the earth's rotation has diminished, its crust must have shrunk, because the form of the earth became less spheroidal, and the increase of gravity increased its density. Recent studies imply that the effect of this was probably small.

Sphericity as a factor in deformation. It is obvious that if the earth shrinks, its crust must become too large for the reduced volume, and must be compressed or distorted to fit the shrunken whole. If the radius shortens 5 miles, each great circle must on the average be compressed, wrinkled, or otherwise distorted to the extent of about 31 (5×6.28) miles. If the mountain foldings on any great circle, taken together, show a shortening of 100 miles, the corresponding radial shortening is about 16 miles. A segment 3,000 miles across (about $\frac{1}{8}$ of a circumference of the earth), such as the bottom of the North Atlantic basin, sinking three miles (about the full depth of the basin), would give a lateral thrust of about 2.3 miles, a little over a mile on each side, a trivial amount compared with the foldings on the adjacent continental borders.

Each portion of the crust of the earth is ideally an arch or dome. When broad areas like continents are considered, it is the dome rather than the arch that is involved, and in this the thrust is ideally toward all parts of its periphery. A dome corresponding to the sphericity of the earth, formed of firm crystalline rock of the high crushing strength of 25,000 pounds to the square inch, and having a weight of 180 pounds to the cubic foot, would, if unsupported below, sustain *only* $\frac{1}{525}$ of its own weight.¹ This result is essentially independent of the extent of the dome, and also of its thickness, provided the former is continental, and the latter does not exceed

¹ Calculations by Hoskins.

a small fraction of the earth's radius. Roughly speaking, each mile of thickness may be conceived to support a layer of about 10 feet of its own material. It is clear therefore, that a dome of shallow depth could not accumulate the stresses involved in the folding of great mountain systems, and that something more than a mere crust of the earth has been involved in the great deformations. But if the great dynamic forces which have deformed the body of the earth have acted through some large part of its depth, and if the rigidity of the interior is as high as the astronomical behavior of the earth implies, its resistance to deformation would be adequate to accumulate such stresses as are required.

The weakness of the crust alone is such that the conclusion seems imperative that, while the pliant subject of minor and frequent warpings, it is wholly incompetent to be the medium of the great deformations. Such deformations apparently involve a large part of the body of the earth, and imply a high state of effective rigidity.

A few references on crustal movements. Lyell, *Principles of Geology*, Vol. II, p. 235; Reade, *Origin of Mountain Ranges, and Evolution of Earth Structure*; Fisher, *Physics of the Earth's Crust*; Dutton, *Greater Problems of Physical Geology*, Bull. Phil. Soc. of Washington, Vol. XI, p. 52; also Am. Jour. of Sci., Vol. VIII (1874), p. 121, and *Geology of the High Plateaus of Utah* (1880); Dana, *Manual of Geol.*, 4th ed., p. 345 et seq.; Woodward, *Mathematical Theories of the Earth*, Smithsonian Rept. for 1890, p. 196; Willis, *The Mechanics of the Appalachian Structures*, 13th Ann. Report, U. S. Geol. Surv., Pt. II (1893), pp. 211-282; LeConte, *Theories of Mountain Origin*, Jour. Geol., Vol. I (1893), p. 542; Gilbert, Jour. Geol., Vol. III (1895), p. 333, and Bull. Phil. Soc. of Washington, Vol. XIII (1895), p. 31; Van Hise, *Earth Movements*, Trans. Wis. Acad. Sci., Arts and Let., Vol. II (1898), pp. 512-514; *Estimates and Causes of Crustal Shortening*, Jour. Geol., Vol. VI (1898), U. S. Geol. Surv. (1904), pp. 924-931; A. Geikie, *Text-book of Geology*, 4th ed., pp. 672-702; Chamberlin and Salisbury, *Geology*, Vol. I, Chapter IX.

Map work. Various phases of diastrophism are shown on the maps of the U. S. Geological Survey listed on pages 432-433 of Salisbury's *Physiography*, Advanced Course. Plates CLXV to CLXVII of Professional Paper 60 show certain topographic features due to faults. The folios, especially of mountain regions, afford other illustrations, best seen in the Structure Section Sheets.

CHAPTER X

VULCANISM

The term vulcanism is here used to include all movements of lava toward the surface of the earth, as well as certain other phenomena connected with these movements. The rise of lava assumes two general phases. The one includes movements by which lava reaches the surface, giving rise to eruptive or volcanic phenomena; the other, movements by which lavas intrude themselves into the outer formations of the earth and congeal underground. The first gives rise to *volcanic* rocks, and the second to *plutonic* rocks. The first are *extrusive*; the second, *intrusive*; the first constitute *eruptions*; the second, *irruptions*. The fundamental nature of the two phases of vulcanism is the same.

1. INTRUSIONS

Fluid rock forced into fissures and solidified there forms *dikes*; forced into chimney-like passages, it forms *pipes* or *plugs*; insinuated between beds, it forms *sills*; accumulated in considerable bodies which arch the strata up over them, it forms *laccoliths* (Fig. 6); if the overlying beds are faulted up, *bysmaliths*, while in greater aggregations underground, it constitutes *batholiths*. Dikes (Fig. 289) and sills vary greatly in thickness, from inches to hundreds of feet. Batholiths may be many miles across, but their depths are not known. Laccoliths and bysmaliths may be looked upon as small batholiths with special features.

The heating of the adjacent rock by intrusions varies with the mass and temperature of the lava. Thin dikes and sills produce little effect, while greater masses metamorphose the adjacent rock notably. The metamorphism results in part from (1) the heat, in part from (2) the pressure incident to the intrusion, and in part

from (3) the chemical changes stimulated by the heat, water, and gases issuing from the lava, and by pressure in the presence of ground-water.

The total amount of lava which has risen toward but not to the surface far exceeds all that has flowed out at the surface. Intrusions



Fig. 289.—A dike two feet wide, cutting through sandstone. The exposed part of the dike is on land scarcely above the water. Arran, coast of Scotland. (H. M. Geol. Surv.)

sions are usually seen only after erosion has removed the rocks which overlay them.

There appear to be certain cases where the intrusion comes so near the surface as to develop explosive phenomena without the extrusion of lava. From the nature of the case this is an inference rather than a demonstration. It is certain, however, that occasional violent explosions take place where no lava comes to the surface. The explosion may be due to the intrusion of lava, or it may be

due to the penetration of surface-waters to hot rocks that have remained uncooled from previous volcanic action. The contact of the water with the hot rock may develop a volume of confined steam sufficient to cause the explosion. A case of this kind occurred in 1888 at Bandai-San in Japan, where there was a sudden and violent explosion which blew away a considerable part of the side of a volcanic mountain which had not been in eruption for at least a thousand years. The mass and violence of the exploded material was such as to fill the air with ashes and debris in a fashion altogether similar to a typical volcanic eruption. The eruption was confined to one explosion, and within a few hours the cloud of dust had disappeared and the phenomenon was ended. No lava was extruded.

Another illustration is perhaps furnished by Coon Butte, Arizona.¹ This "butte" consists of a rim of fragmental material encircling a crater-like pit from which the fragments were obviously ejected by an explosion. The pit is in sedimentary strata, and the material of the rim is composed of fragments of the sedimentary rock thrown out of the pit. The volume of the material in the rim is in keeping with the size of the pit. No igneous rocks appear in the pit or about it, though there has been igneous action in the vicinity. The cause of the explosion is not demonstrable, and it may be an error to connect it with an intrusion of lava below. Fragments of meteorites were found about the butte, but this association may be accidental or causal. It has been suggested that a large meteorite fell at the site of the butte, and penetrating the earth a few hundred feet, exploded.² This sequence of events would account for the pit and the rim.

2. EXTRUSIONS

When molten rock is forced to the surface it gives rise to the most intense and impressive of all geological phenomena. The energies acquired in the interior under great compression here find sudden relief. Enclosed gases often expand with extreme violence,

¹ Gilbert, 14th Ann. Rept., U. S. Geol. Surv., Pt. I, p. 187.

² Fairchild, Bull. G. S. A., Vol. XVIII, p. 493.

hurling portions of lava to great heights and shattering them into fragments, special forms of which are called bombs, cinders, ash, etc., all of which constitute *pyroclastic* material. Much of the explosive violence of volcanoes has been attributed to the contact of the hot rising lava with ground-water, but the function of ground-water in the explosions has probably been exaggerated.

There are two phases of extrusion, and at their extremes they are strongly contrasted. The one is explosive ejection, often attended with great violence; the other a quiet out-welling of the lava. More or less closely related to these two phases of extrusion are two classes of conduits, the one, *restricted openings*, often pipes, ducts, or limited fissures, from which the amount of lava extruded is relatively small, and hence it congeals near the orifice, forming cones; the other, *great fissures* out of which the lava pours in great volume and from which it spreads over wide tracts, often in broad thin sheets. There is no fundamental difference between great fissure eruptions and the eruptions of restricted vents, and the two types blend. The extent of the spreading of lava into thin sheets is due more to the mass and the fluidity of the lava than to the form of the outlet. The stupendous outflows of certain geologic periods appear to have issued mainly from extended fissures.

a. *Fissure Eruptions*

The chief known fissure eruptions of recent times are the vast basaltic floods of Iceland; but at certain times in the past there have been prodigious outpourings of lava, flow following flow until formations thousands of feet thick and covering thousands of square miles, were built up. One of these occurred in Tertiary times in Idaho, Oregon, and Washington (Fig. 290), where about 200,000 square miles were covered with sheets of lava, aggregating in places some 2,000 feet in thickness. Still earlier, in the Cretaceous period, there were enormous flows on the Deccan, covering a like area to the depth of 4,000 to 6,000 feet. Still earlier, in the Keeweenawan period, an even more remarkable succession of lava-flows in the Lake Superior region developed a series of igneous rocks of almost incredible thickness. In these cases there is little evidence of explosive or other violent action. There are but few

beds of ash, cinders, or other pyroclastic material. The inference is, therefore, that the lavas welled out quietly, and flowed over the surrounding country. For the most part these wide-spreading flows are composed of basic material, which is more easily liquefied and more fluent at a given temperature than the acidic lavas. The latter are more disposed to form thick bodies near the point of extrusion.

Massive outflows of this class are the greatest examples of extrusions, though they are not now the dominant type. It has

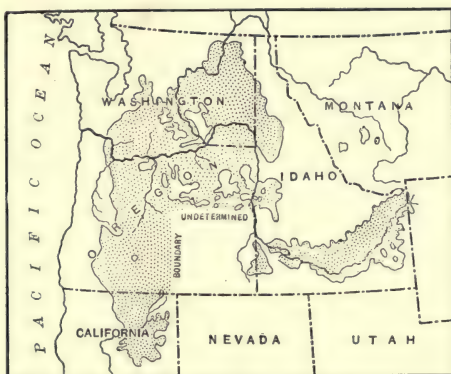


Fig. 290.— Lava-flows of the northwestern part of the United States.

been thought that the volcanic type of extrusion followed the fissure eruptions as a phase of decline; but this view has not been substantiated.

b. *Volcanoes*

A volcano is a circumscribed vent in the earth's crust, out of which hot rock, gases, and vapors issue. The material is generally built up into mounds or cones (Figs. 291–293). These cones are often called volcanoes, though they are really the results of volcanic activity. So long as a volcano is active there is likely to be a depression, or *crater* (Fig. 294), in the summit of its cone. The crater connects downward with the source of the lava at an unknown depth. Craters may be a mile or more across, but they are usually smaller, some much smaller. After sufficient erosion,

extinct volcanoes show that the former passageways, leading down toward the sources of the lava, vary much in size and shape, and usually have diameters smaller than the craters.

The exact number of volcanoes now active cannot be stated precisely, because most volcanoes are in action only at more or less distant periods, and it is impossible to say whether a volcano that is now quiescent is extinct or only resting. It is quite safe



Fig. 291.— Cinder cone forming the summit of Mt. Vesuvius

to include at least 300 in the active list, and the number may reach 350 or more. The number that have been active so recently that their cones remain distinct is several times as great.

Distribution of Volcanoes

1. **In time.** In the earliest known ages, igneous action appears to have been very widespread. No great area of the oldest (Archæan) rocks is now known where the formations are not largely igneous, either of the intrusive or of the extrusive kind. From the Paleozoic to the present, the distribution of volcanic action over the surface seems to have been, in a general way, much what it is to-day; that is, certain areas were affected at times by vol-

canoes, while other and larger areas had few or none. This is not equally true of all periods, as will be seen in the historical studies that follow. There were periods when volcanic activity was widespread and energetic, and other periods when it was limited in amount and in distribution. The known facts do not indicate a

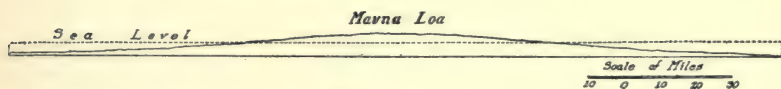


Fig. 292.— Profile of the cone of Mauna Loa. Vertical scale same as horizontal. (U. S. Geol. Surv.)

steady decline in volcanic activity, but rather a periodicity; at least this is so for the portion of the globe that is now known well enough to warrant conclusions. One of the greatest of the volcanic periods falls within the Cenozoic era, just preceding the present geological period, and the volcanic activity of the present is perhaps but a declining phase of the activity of that time.



Fig. 293.— Cinder cone.

2. **Relative to land and sea.** The active volcanoes of the present time are located chiefly along the borders of the continents, and within the great oceanic basins (Fig. 295). On this account, the sea-water has often been supposed to have some causal connection with volcanic action, and the presence of chlorine in the volcanic gases has been urged in support of this view. Volcanoes, however, are not distributed so equably and exclusively about the several oceans as to give this conclusion force, though the basins, as basins, probably favor vulcanism. Volcanoes are numerous within and around the Pacific, the greatest of the oceans; but they are not especially abundant in or about the Atlantic, while they are

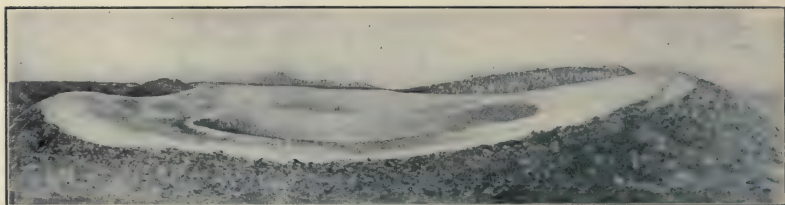


Fig. 294.—Sketch of the crater of cinder cone near Lassen Peak, Cal., showing the peculiar feature of two rings. The funnel is 240 feet deep. (U. S. Geol. Surv.)

numerous in and around the Mediterranean, a much smaller body of water. On the other hand, there are existing or very recent volcanoes in the interior of Asia, Africa, and America. If volcanoes were dependent upon proximity to the sea, they should have had close relations to it in the past, as much as now; but in recent periods there has been much volcanic activity in the plateau region and even in the plains region of western America, and in the heart of Asia and Africa, far from the ocean. In older periods, it is still less clear that there was any connection between volcanoes and surface waters.

3. **Relative to crustal deformations.** The distribution of present and recent volcanoes is much more suggestively associated with those portions of the crust *that have undergone movement in comparatively recent times, or are still moving.* The great mountain belt stretching from Cape Horn to Alaska and thence onwards

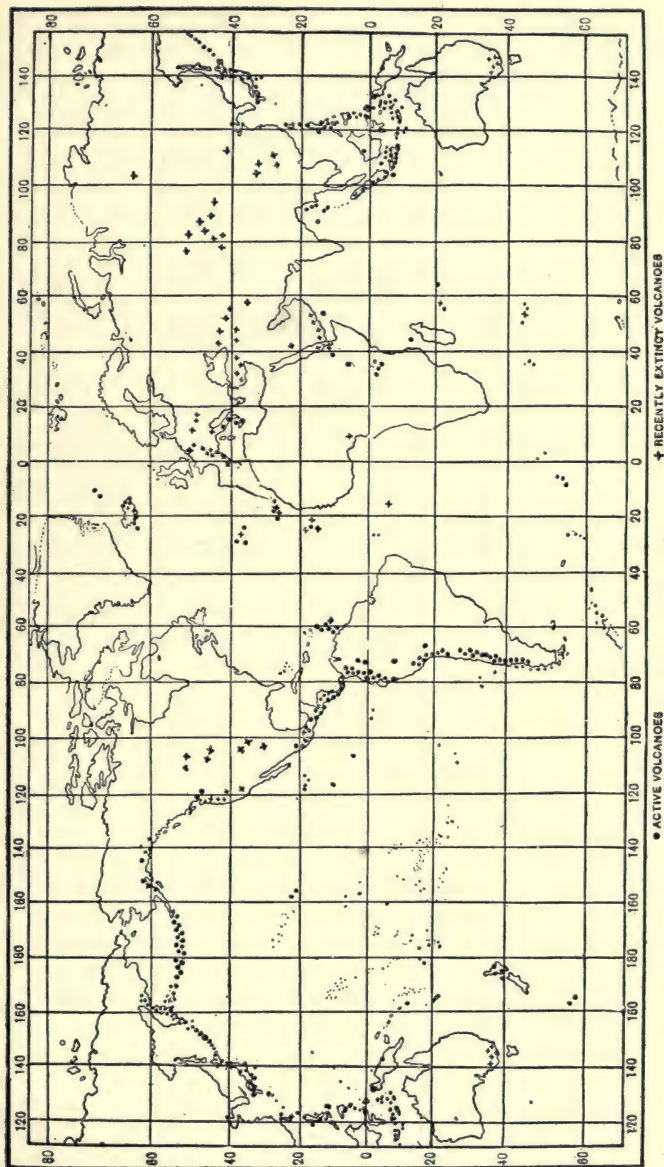


Fig. 295.— Map showing distribution of volcanoes. (After Russell.)

along the east coast of Asia is dotted with active and recently extinct volcanoes. The tortuous zone of mountainous wrinkles that borders the Mediterranean, and stretches thence eastward to the Polynesian Islands, is another notable volcanic tract. These two belts include the greater number of existing and recent volcanoes on the land.

4. **In latitude.** The distribution of volcanoes appears to have no specific relation to latitude. Mounts Erebus and Terror amid the ice-mantle of Antarctica, and Mount Hecla in Iceland, as well as the numerous volcanoes of the Aleutian chain, give no ground for supposing that volcanoes shun the frigid zones, while the numerous volcanoes of the equatorial zone imply that they do not avoid the torrid belt.

5. **In curved lines.** In the Antilles, the Aleutian Islands, the Kurile Islands, and in some other tracts, there is a linear arrangement of volcanoes, with appreciable curvatures, the convexities of which are turned toward the adjacent ocean. In other cases there is a linear arrangement without appreciable curvature, as in the Hawaiian range. Less often, volcanoes are bunched irregularly, as in some of the groups of volcanic islands of the Pacific (Fig. 295).

The Relations of Volcanoes

A significant feature in connection with volcanoes is the apparent sympathy between adjacent vents in some cases, and their entire independence in others. The recent outbursts in Martinique and St. Vincent, and the concurrent symptoms of activity in other places, seem to point clearly to sympathy. On the other hand, the independence of neighboring vents is sometimes extraordinary, as those of Mauna Loa and Kilauea in Hawaii. These two volcanoes are only about twenty miles apart, the one on the top and the other on the side of the same great mountain mass. The crater of Loa is about 10,000 feet higher than that of Kilauea, and yet, while the latter has been in constant activity as far back as its history is known, the former is periodic. The case is the more remarkable because of the greatness of the ejections. The outflow of Mauna Loa in 1885 formed a stream 3 to 10 miles in width, and 45 miles in length, with a probable average thickness of 100 feet, and some

of its other outflows were nearly as massive. Besides this massiveness, there were extraordinary movements of the lava within the crater, if the testimony of witnesses may be trusted. But throughout these great movements in the higher crater, the lava-column of Kilauea, 10,000 feet lower, continued its quiet action without sensible relation to its boisterous neighbor. No difference in specific gravity that could at all account for a difference in height of 10,000 feet has been observed or can be presumed. It seems a necessary inference, therefore, that the two lava-columns have no connection with each other, or with a common reservoir. The tops of some lava-columns stand about 20,000 feet above the sea, while others emerge on the sea-bottom far below sea-level. The total vertical range of emergence is between 30,000 and 40,000 feet, a difference which tells its own story as to their relative independence.

Trivial agencies. Eruptions seem to be somewhat more common when atmospheric pressure is high than when low, doubtless because the increased atmospheric weight on a large area of the crust, aids in forcing out the lava or the volcanic gases. This can only be effective when other forces have almost accomplished the result. Eruptions seem also to be more common when tidal strains favor them, for like reasons. In the same class are probably to be put the effects of heavy rains. Such factors are to be regarded as mere incidents, of no moment in the real causation of vulcanism, but of some value in determining the precise moment of eruption.

Periodicity. Most volcanoes are intermittent in their action, long periods of dormancy intervening between periods of activity. Volcanoes supposed to be extinct may renew their activity, occasionally with terrific violence. Their periodicity awaits an explanation, but the temporary quiet very likely means an exhaustion of the supply of gas or of lava, or of both, to which the active stage is due.

Products of Volcanoes

Pyroclastic material. The fragmental materials which are blown out of a volcano are, as a rule, portions of lava which solidified before ejection, or during their flight in the air. Masses of rock

tons in weight are sometimes thrown out, and from masses of such size, the fragments grade down to minute particles of dust. The dust particles (often called *ash*) are thrown high into the air in some cases, and, caught by the winds, are shifted incredible distances, as already noted (p. 89). While, therefore, the fluid lava and the larger fragmental materials ejected from the volcano stay near the vent, the fine materials are scattered broadcast.

Liquid rock, lava. The term lava is applied to all kinds of liquid rock which issue from a volcano, and also to the solid rock



Fig. 296.— The edge of an old stream of lava, showing (1) its broken character due to movement after the outside had hardened, and (2) the steep slope of the stream of stiffened lava. Near Flagstaff, Ariz. (Fairbanks.)

formed when this congeals. Lava never flows so freely as water, and it is sometimes very stiff or viscous. The distance to which it flows depends on its liquidity, its amount, and the slope of the surface on which it is poured out. The more fluid the lava, the greater its amount, and the steeper the slope on which it flows, the farther it will move.

As lava flows, its upper surface may cool so much as to become

hard while the interior is still fluid. The fluid part may then break out at the side or end of the hardened shell and flow away, leaving a hollow crust of solidified lava. On further cooling, the shell contracts and cracks, and often caves in. The hardened surface of a lava-flow may be broken by the movement of the fluid lava below, and the solid fragments be displaced and upturned so as to give the surface a jagged appearance.

Lava takes on various phases as it becomes solid. If it hardens under little pressure, or at the surface, the gases and vapors which it contains may expand so that it is converted into a sort of solidified rock froth, called *scoria*; or if the pores are very small, *pumice*. If the lava solidifies quickly without becoming frothy, it usually makes *volcanic glass* or *obsidian*. If the lava cools slowly under pressure, the substances of which it is composed usually crystallize into various minerals. The kinds and proportions of the minerals depend chiefly upon the composition of the lava.

Gases and vapors. The gases and vapors which issue from volcanoes are of many kinds. Among the commoner ones are those of water (H_2O), carbon dioxide (CO_2), chlorine (Cl), hydrochloric acid (HCl), sulphur dioxide (SO_2), and hydrogen sulphide (H_2S); but with these more important ones there are many others. Some of the gases are poisonous, and, as in the case of Pelée, their temperature is in some cases so high as to be destructive to life.

Formation of Cones

Lava-cones. The lava usually flows away from the vent in streams which solidify before running far. As the lava-streams flow in different directions at different times, the total effect is a low cone formed of tongues of lava radiating from the point of exit. The streams often congeal before they reach much beyond the base of the cone, and not rarely while they are yet on its slope. So far, therefore, as the volcanic cone is formed of lava, it has a radiate structure made up of a succession of congealed lava-streams. In these cases the slopes are low, because the fluidity of the lava prevents the development of high gradients. It is, however, the exception rather than the rule, that the cone is made up mainly of lava-streams, though the great Hawaiian volcanoes are of this class.

The form of the cone, when composed chiefly of lava, is also affected by the mass of the outflow and by its fluidity. Other things being equal, the larger the outflow at a given time, the more widely it distributes itself, and the flatter the cone. As a rule, basic lava cones are flatter than the cones of acidic lavas.

Cinder-cones. The larger portion of the lava blown into the air by the expanding gas-bubbles falls back in the immediate



Fig. 297.— Spatter-cone and cavern. Kilauea, Hawaii. (Photo. by Libbey.)

vicinity of the vent and builds up a cinder-cone. From the nature of the case, this fragmental matter is often disposed symmetrically, making a cone with steep slopes (Fig. 291).

Small or temporary vents formed as offshoots from the main vents often give rise to secondary or "parasitic" cones. These are sometimes numerous, as in the case of Etna, and they may be so important that a volcanic mountain becomes a compound cone. A still more subordinate variety consists of "spatter-cones" formed about small vents that eject little dabs of lava which form chimneys, cones, domes, etc. Spatter-cones (Fig. 297) often arise from the surface of the lava-flows themselves.

From most existing volcanoes both lava-flows and fragmental ejecta are given forth, and the resulting cones are composite in material. The lava breaks through the side of the cone more



Fig. 298.— The eruption cloud of Pelée, December 16, 1902. (Lacroix.)

frequently than it overflows the summit, and this gives rise to irregularities of form and structure. The cones are also subject to partial destruction both by outbursts of lava and by explosions.

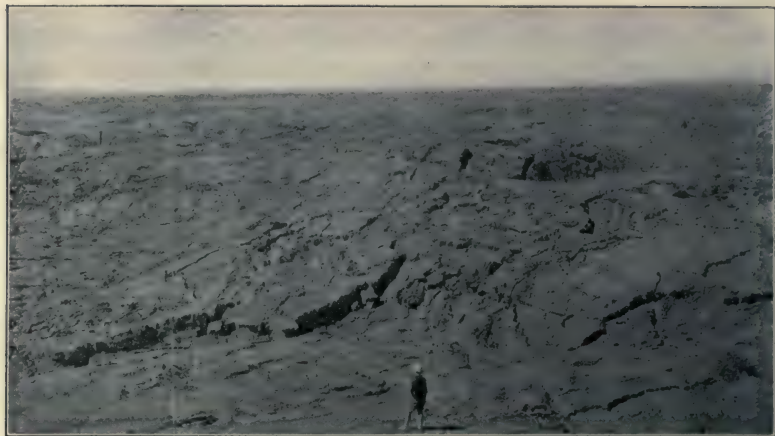


Fig. 299.— Relatively smooth lava surface near the Jordan craters, Malheur Co., Ore. (U. S. Geol. Surv.)



Fig. 300.— Ropy surface of lava, Mauna Loa, flow of 1881. (Calvin.)

As a result, many volcanic regions show old, partially destroyed craters, as well as new and more perfect ones.

In violent eruptions, the steam, accompanied with much ash, is shot up to great heights, often rolling outwards in cumulus or cauliflower-like forms (Fig. 298). In the more violent explosions, these columns are projected several miles. In the phenomenal case of Krakatoa, the projection was estimated at seventeen miles. The steam, by reason of its great expansion as it rises, and by its contact with the colder air, is condensed quickly, and prodigious floods of rain frequently accompany an eruption. This rain, carrying down a portion of the ash and gathering up much that had previously fallen, gives rise to *mud-flows*, which in some cases constitute a large part of the final deposit. These mud-flows lodge chiefly on the lower slopes of the cone or adjacent to its base.

A portion of the finer exploded material floats away in the air to greater or less distances, and forms widespread *tufa-deposits*. In some cases, beds of volcanic ash many feet in thickness (as those of Nebraska) are found far from any known volcanic center. The extremely fine ash from the great explosion of Krakatoa floated several times around the earth in the equatorial belt, and spread northward into the temperate zones.

Lavas

Their nature. The nature of lavas and of the rocks derived from them was discussed in chapter II. In view of prevalent misconceptions, it may be repeated that *lavas are solutions of mineral matter in mineral matter, rather than simply melted rock*. Gases, as well as rock materials, enter into this mutual solution. The distinction between such solutions and molten rock is not very sharp, but it is essential to know that the order in which the minerals crystallize from lavas is not dependent simply on their melting temperatures. It appears rather to depend on the order in which the solution becomes saturated with the constituents of each of the several minerals. For example, quartz, which has a very high melting-point, often crystallizes out from the lava much later than minerals which have lower melting temperatures. The solutions are exceedingly complex, and include a wide range of chemical

substances. Chief among them, as already stated, are silicates of aluminum, potassium, sodium, calcium, magnesium, and iron, with minor ingredients of nearly all known substances. The stages at which saturation for certain compounds is reached vary somewhat widely.

The old idea that lava is melted rock, is not, however, to be abandoned wholly. Lava sometimes solidifies much as water freezes. Thus when lava is suddenly cooled, the congelation is essentially the solidification of a melted substance. The result is a glass, every part of which has essentially the same composition that the liquid had. Even in this case, however, some of the gases escape. If the cooling is slower, the various substances in the mixture crystallize out into minerals in the order in which they severally reach saturation. This involves the principle that solubility is dependent on temperature, and that as the temperature sinks the degree of solubility declines, and the saturation-point for some constituents of the solution is reached earlier than that for others. With sufficiently slow cooling, all the material passes into the solid state by the crystallizing of the several minerals in succession. This does not mean that two or more minerals may not be forming at the same time, but it does mean that some minerals may be crystallized out while the surrounding material is still fluid. In most igneous rocks, nearly perfect crystals of certain minerals are common, while other minerals, crystallizing later, adapt themselves to the space left. This conception is supported by the fact that lavas, while still in the fluid condition, often contain well-formed crystals, and these crystals sometimes make up a considerable part of the flowing mass, very much as water in certain conditions may be filled with crystals of ice.

The temperature of lava. Accurate determinations of the temperatures in the centers of lava-columns, where they have been least reduced by contact with the rock-walls, have not been made; but it is clear from the white heat of some lavas that their temperatures are often appreciably above the melting-point. This is also a necessary inference from the length of time lavas remain fluid, notwithstanding the great surface of contact of the column in its miles of ascent, the conversion into steam of the water in the rock

through which the lava passes, and the expansion and escape of the gases. In cases where determination has been practicable, it has been found that the melting-points of silver (about 960°C.) and copper (about $1,060^{\circ}\text{C.}$) are reached. From these and other facts it is probably safe to assume that the original temperatures of the lavas as they rise to the surface are sometimes considerably above $2,000^{\circ}\text{Fahr.}$ ($1,093^{\circ}\text{C.}$). Even such a temperature must be somewhat below the original temperature of the lava, because some heat must be lost in rising, both by contact with the walls of the colder rocks, and by the expansion of the gases within them. If any considerable part of these gases is derived from waters which join the lava in its upward course, the energy consumed in raising the water to the high temperature of the lavas must be subtracted from the original heat, and must be a further source of reduction of temperature. It seems probable that temperatures as high as those necessary for ordinary fusion, and perhaps even higher, are attained by the lavas at their sources.

Depth of the source of lavas. Attempts have been made to determine the depth from which lavas rise, by calculations based on the earthquake tremors that accompany eruptions; but such calculations really tell very little concerning the true point of origin of the lava. At most they probably tell merely where the ascending lava begins to *rupture* the rock through which it passes, and rupture may not be possible below the zone of fracture, which is probably not more than six miles deep. In the zone of flowage below, where the pressure is too great to permit fracture, the lava not improbably makes its way by some boring or fluxing process, which might not be capable of giving rise to seismic tremors. The tremors perhaps compel us to place the beginning of movement of lava *at least as low as the bottom of the fracture zone*, but they probably offer no sufficient ground for limiting the lava's origin to this or any other specific depth.

Volcanic Gases

One of the most distinctive features of volcanoes is the explosive action arising from the gases and vapors pent up in the lava. The precise way in which they are held has not been determined. It has

been thought that lava spontaneously absorbs gases, especially when the gases are under great pressure, and that as the pressure is relieved and the lava cooled and solidified, the larger part of the gases escape. In those cases in which the eruption is quiet, the escape of the gases is but partial while the lava is in the crater, and much gas remains to be given off after the lava has been extruded and is about to congeal. The gases are then given off slowly and quietly. If, however, the lava is surcharged with gases, and if their escape is retarded by the viscosity of the lava, they gather in large vesicles or bubbles in the lava in the throat of the volcano, and on coming to the surface explode, hurling the enveloping lava upwards and outwards, often to great distances. The violence of the explosion reduces a portion of the lava to the fineness of dust, — the “ash” and “smoke” of the volcano. Portions of the lava may be inflated by the gases without being blown to bits, forming *pumice* and *scoria*, as already noted. Masses of lava that have solidified into more or less rounded masses in the crater are hurled out as *bombs*, and not infrequently portions of the walls of the crater or of the duct below are broken off and shot forth.

Differences in gas action. The causes of the differences of gas action in different volcanoes are undetermined, but the following suggestions may point to a part of the truth: (1) Some lavas contain more gases than others, and hence are predisposed to be more explosive; (2) some are more viscous than others and hence hold the gases more tenaciously until they accumulate and acquire explosive force, while the more liquid lavas allow their gases to escape more freely; (3) probably a main occasion of violent explosions lies in the fact that the lavas have begun to crystallize while yet in the volcano. When the crystals form in the magma, they exclude the gases which were in the substance from which they are developed, and this excluded gas overcharges the remainder of the lava. This view is supported by the fact that the pumice and ash of such extraordinarily explosive eruptions as those of Krakatoa and Pelée contain many small crystals which had certainly formed before the explosion took place. Incipient crystallization does not, however, appear to be a universal accompaniment of explosive action.

The discharge of the gases is often spasmodic, and usually consists of a succession of distinct explosions. In some cases the explosions follow one another at rather constant and frequent intervals, as in Stromboli, where they occur at intervals of three to ten or more minutes. In others the spasms are distant and irregular.

Kinds of gases. Steam is the chief volcanic gas. Free hydrogen and oxygen are present also, and are perhaps the result of the dissociation of steam at the very high temperature of the lava. Carbon dioxide is probably next in abundance, and carbon monoxide is present. Sulphur gases (sulphuretted hydrogen, sulphurous acid, and perhaps sublimated sulphur) are common accompaniments of volcanic eruptions. All of the sulphurous gases are liable to pass into sulphuric acid by oxidation and hydration. Chlorine and hydrochloric gases are also common, particularly at high temperatures. Certain gases, such as hydrogen, chlorine, hydrochloric acid, and some of the sulphurous gases, are especially associated with high temperatures, and are perhaps dependent on them. Sulphuretted hydrogen, on the other hand, is commoner at lower temperatures. Oxygen, nitrogen, and probably carbon dioxide or carbon monoxide are present throughout all ranges of temperatures. The gases mentioned above are the more abundant ones in lavas, but the list is not exhaustive.

Gases in volcanic rocks. Igneous rocks contain gases, often in large quantities.¹ When the lavas lodge underground without free communication with the surface, there is reason to think that they retain a larger percentage of their original gases than the lavas which are freely exposed at the surface. At any rate, deep intrusive rocks contain notable quantities of gases. Recent surface lavas also contain gases of similar kinds, but not in equal amount, so far as available analyses show.

Source of the gases. One of the outstanding problems of geology is to determine (a) how far the material of the gases had the same origin as the material of the lavas, and (b) how far the material for the gases penetrated from the surface.

¹ Rollin T. Chamberlin, *Gases in Rocks*, Carnegie Institution, 1908.

The peculiar proportions of the rock-gases, among which hydrogen and carbon dioxide so greatly preponderate, seem to imply that they are not derived chiefly from surface waters or the atmosphere; they appear to be original constituents of the rocks in the main, and when given forth they appear to constitute real additions to the atmosphere.

The Cause of Vulcanism

The explanation of the extraordinary facts involved in volcanic phenomena is wrapped up in that of the origin of the earth, for the agencies which the earth inherited from its birth are beyond doubt factors in vulcanism. This phase of the subject will be treated only briefly here.¹

The explanation of vulcanism involves two essential elements, (1) the origin of the lavas, and (2) the forces by which they are expelled. The current explanations of vulcanism fall into two general classes: (1) those which assume that the lavas are residual portions of an original molten mass, and (2) those which assign the lavas to the local liquefaction of rock.

The view that the lavas are residues of an original molten globe formerly prevailed, but is found to encounter grave difficulties because of the independent action of vents which are closely adjacent to one another. When the lava columns vary thousands of feet in height on the same mountain mass, as in the Hawaii volcanoes, even a resort to the hypothesis of local residual reservoirs is not altogether satisfactory. Another view which has had much currency supposes that surface water and its absorbed gases penetrate to heated rock and are absorbed by it, rendering the whole liquid, and that the lava thus formed is then forced to the surface. The progress of investigation, however, does not support the belief that water penetrates from the surface to depths below the zone of fracture, and hence is far from reaching highly-heated rocks. The gases of volcanoes and of igneous rocks are not sufficiently like those of water to support this view.

The relief of pressure, which lowers the melting point of rock,

¹ For fuller statement see the authors' larger work, Vol. I, pp. 395-607, Vol. II, pp. 99-106, 116-118, 120, 130.

when felt by rocks already heated above what would be their melting points at lowered pressures, has been held to be a possible cause of vulcanism. Such relief of pressure is assigned to faulting and denudation. But many volcanoes are located in the bottom of the ocean, where denudation does not take place, and faulting that would give relief of pressure is not always related to vulcanism in any clear way. Melting by crushing has been suggested, but in the deeper parts, crushing involves increase of pressure, which opposes melting. Depression to the zone of high temperature, under accumulated sediments, is also assigned as a cause of melting, but there is very little sedimentation in the ocean far from land where many volcanoes are situated.

If the earth grew up by slow accessions of matter, and if its interior heat is due chiefly to the internal *compression* resulting from growth, the distribution of internal temperature would be as shown in Fig. 288, p. 362. With like conductivity, the flow of heat from the deep interior to the middle zone of the earth would be greater than the loss from this zone to the superficial shell. The middle zone might thus rise in temperature. This zone is, under this view, supposed to be composed of various kinds of matter, mixed as they happened to fall in. If the temperature rises, the fusion-points of some of these constituents will be reached sooner than those of others. A fusion or solution of the more soluble portions may thus take place while the rest of the rock remains solid. To the liquid part the gases and volatile constituents in the original material would obviously unite, as being also liquefiable parts. With a continued rise of temperature, the liquefaction would extend itself until adjacent pockets or threads of lava found means of uniting, and the lighter portions of the fluid would be forced upwards and work their way toward the surface by fusing and fluxing.

As these portions rise, the pressure upon them becomes less and less, and hence the temperature necessary for liquefaction gradually falls, leaving them a constantly renewed margin of temperature available for melting their way through the upper horizons. Thus it is conceived that these fusible and fluxing selections from the middle zone might thread their ways up to the zone of fracture,

and thence, taking advantage of fissures and fractures, reach the surface (Fig. 301). It is conceived that such liquefaction and extrusion would carry the excess of temperature received by the

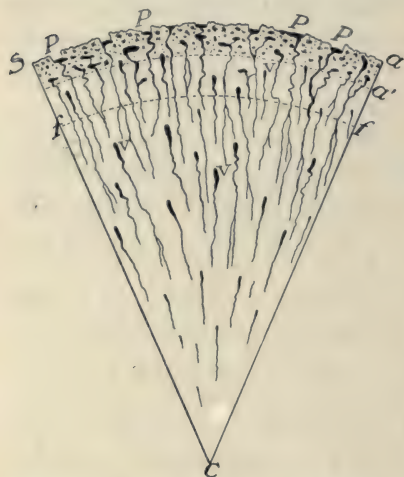


Fig. 301.— Ideal section of a portion of the early earth, illustrating its assigned modes of vulcanism. *C*, center; *S*, surface; *a-a'*, fragmental zone; *a'-f*, zone of continuous rock below surface melting temperature; *ff-c*, interior portion whose temperatures rise from the surface melting-point at *f-f* to a maximum at *C*; *V, V*, threads or tongues of molten rock rising from the interior to various levels, many of these lodging within the fragmental zone as tongues, batholiths, etc.; *PPP*, explosion pits formed by volcanic gases derived from tongues of lava below.

middle zone from the deeper interior, out toward the surface, or even to it. The outward movement of the lava would tend to regulate the temperature of the middle zone, forestalling general liquefaction, and keeping the zone as a whole solid. The independence of volcanoes is assigned to the independence of the liquid threads that work their way to the surface. Nothing like a reservoir or molten lake enters into the conception. The prolonged action of volcanoes is attributed to the slow feeding of the liquid threads from the middle zone, which is liquefied in spots only. The frequent pauses in volcanic action are assigned to temporary deficiencies of supply, and the renewals to the gathering of new supplies after a sufficient period of accumulation.

The distribution of volcanoes

in essentially all latitudes and longitudes is assigned to the general nature of the cause. The special surface distribution is assumed to be influenced, though not altogether controlled, by the favorable or unfavorable conditions for escape presented at different places. The persistence of volcanic action in time is attributed to the magnitude of the interior source, to its deep-seated position, and to the slowness of conduction of heat from the

earth's interior. The force of expulsion is found in the stress-differences in the interior, particularly the periodic tidal and other astronomic stresses, and in the slow pressure brought to bear on the slender threads of liquid by the creep of the adjacent rock. The violent explosions are due to the included gases, of which steam is chief. Little efficiency is assigned to surface-waters, and that little is regarded as secondary and incidental. The true volcanic gases are regarded as coming from the deep interior, and as being after expulsion, accessions to the atmosphere and hydrosphere. The standing of the lavas in volcanic ducts for hundreds and even thousands of years with only little outflow, as in some of the best-known volcanoes, is regarded as an exhibition of an approximate equilibrium between the hydrostatic pressure of the deep-penetrating column of lava, and the flowage-tendency of the rock-walls, the outflow being also conditioned on the slow supply below, and on the periodic stress-differences of the interior.

For the present, volcanic hypotheses must be left to work out their own destiny, serving in the meantime as stimulants of research. All but the last have been long under consideration. The recent discovery of the heating effects of radioactivity has given rise to the hypothesis that the origin of lavas is due to this cause. It seems clear that this must at least be a cooperative agency. It is too early in the new investigation to decide whether it can wisely be regarded as the sole cause or even an essential one.

Modes of Reaching the Surface

All views that locate the origin of the lavas deep in the earth must face the difficulty of the passage of lava through the zone of the earth below the fracture zone. Near the surface, the lavas usually take advantage of bedding-planes, or of fissures already existing, or made by themselves. There is little evidence that they bore their way through the zone of fracture by melting, though they round out their passageways into pipes as they use them, much as streamlets on glaciers falling into crevices round out moulins. But this use of fissures and bedding-planes for passage is probably merely a matter of least resistance where the lavas are

relatively cool, and their capacity for melting is low, or perhaps even gone.

In the denser and warmer zone below, the alternatives seem to be (1) melting or fluxing, or (2) mechanical penetration without fracture. As rocks "flow" in this zone by differential pressure without rupture, an included liquid mass may be forced to flow through the zone by sufficient differential pressure. If local differential pressures at the surface are neglected as probably incompetent,



Fig. 302.— Mount Baker, Wash. An old volcanic cone. (Copyright, 1906, by Kiser Photo. Co., Portland, Ore.)

there only remain the stress-differences of the interior, and the differences of hydrostatic pressure between the lava-column and the surrounding solid columns. The latter would not be great until a column of liquid of much depth was formed, and the former would probably not be concentrated on the liquid in such a way as to force it bodily through the solid rock. Probably fusing or fluxing its way with the aid of stress-differences is the chief cause of the rise of lava below the zone of fracture. In this it may be supposed to be assisted by its gases, by its selective fusible and fluxing nature, by its very high temperature if it comes from very great depths, and by the stress-differences which attend tidal strains in the deep interior. In ascending from lower to higher

horizons, the lava would be constantly invading regions of lower melting-point, because of lesser pressure, and thus always have an excess of heat above the local melting temperature until it invaded the external, cool zone. From that point on, the rising lava must constantly lose portions of its excess of temperature by contact with cooler rocks. If its excess of temperature is insufficient to enable it to reach the zone of fracture, the ascending column is arrested and becomes plutonic rock. If it suffices to reach the zone of fracture, advantage may be taken thereafter of fissures, and the problem of further ascent probably becomes chiefly one of hydrostatic pressure, in which the ascent of the lava-column is favored by its high temperature and its included gases. The hydrostatic contest is here between the lava-column *measured to its extreme base*, and the adjacent rock-columns *measured to the same extreme depth*. The result is, therefore, not necessarily dependent on the flowage of the outer rocks, but may be essentially or wholly dependent on the deep-seated flowage of the rock of the lower horizons. The ascending column may reach hydrostatic equilibrium before it reaches the surface, and may then form underground intrusions of various sorts without superficial eruption, or it may only find equilibrium by coming to the surface and pouring out a portion of its substance and discharging its gases.

References on vulcanism. G. P. Scrope, Volcanoes, London, 1872. C. E. Dutton, Geology of the High Plateaus of Utah, U. S. Geog. and Geol. Surv., 1880. The Hawaiian Volcanoes, Fourth Ann. Rept., U. S. Geol. Surv., 1883. Judd, Volcanoes, 1881; The Eruption of Krakatoa (Com. of the Roy. Soc.), 1888. J. D. Dana, Characteristics of Volcanoes, 1890. Milne and Burton, The Volcanoes of Japan, 1892. J. P. Iddings, The Origin of Igneous Rocks, Bull. Phil. Soc., Washington, Vol. XII, 1892. A. C. Lane, Geologic Activity of the Earth's Originally Absorbed Gases, Bull. Geol. Soc. Am., Vol. V, 1894. A. Geikie, Ancient Volcanoes of Great Britain, London, 1897. I. C. Russell, Volcanoes of North America, 1897. T. G. Bonney, Volcanoes, Their Structure and Significance, New York (and London), 1899. A. Heilprin, Mont Pelée and the Tragedy of Martinique, Philadelphia (and London), 1903. Further accounts of the same volcanoes are found in the Nat'l Geog. Mag., Vol. XIII, 1902 (Russell, Hill, Hovey, Diller, and Hildebrand).

Map work. Plates CLV to CLXIV, of Professional Paper 60, U. S. Geological Survey, illustrate various topographic effects of vulcanism. The Structure Section Sheets of the folios of the Survey, and the maps of various Survey Reports show the many and diverse relations of igneous rocks.

CHAPTER XI

STRUCTURAL (GEOTECTONIC) GEOLOGY

The general method by which rocks are formed has been set forth in previous chapters, and many of their structural features have been touched upon. It remains to assemble the structural features already mentioned and to note certain additional ones.

Sedimentary Rocks

Stratification. Sedimentary rocks are usually arranged in more or less distinct layers; that is, they are *stratified*. Stratification consists primarily in the superposition of layers of different constitution or compactness, on one another; but layers of like constitution or compactness are often separated by films of different material which cause the partings between them. The bedded arrangement of stratified rocks is due to various causes, but primarily to the varying agitation of the waters in which the sediments were laid down. Where the depositing waters are agitated to the bottom, coarse sediment only is likely to be deposited. Where the waters are quiet at the bottom, fine sediment is the rule. Since the agitation of the waters is subject to frequent change, coarser material may succeed finer, and vice versa, in the same place. Hence arise *beds*, *layers*, and *laminæ*. The terms *layer* and *bed* are generally used as synonyms, while *laminæ* are thinner divisions of the same sort. The term *stratum* is sometimes applied to one layer, and sometimes to all the consecutive layers of the same sort of rock. For the latter meaning the term *formation* is often used.

In some cases bedding seems to have been determined by strong currents which temporarily not only prevented deposition over a given area, but even cut away the loose surface of deposits already made, giving a firm surface from which succeeding deposits are

distinct. This sequence of events is sometimes shown by the truncation of laminae, and by other signs of erosion. The commoner sorts of bedded rock are limestones, shales, sandstones, and conglomerates.

The bedding of *limestones* is often caused by films of clayey material between the layers of limestone, the films causing natural



Fig. 303.— Cross-bedded sandstone. Maol Donn, Arran. The diagonal bedding is conspicuous in the lower right-hand part of the figure. (H. M. Geol. Surv.)

partings. Sometimes, however, bedding arises from variations in the physical condition of the calcareous sediment itself. Lamination is not usually conspicuous in pure limestone, though it may be well developed in the shaly phases of this rock. *Shales* are normally laminated as well as bedded, and the lamination is often more notable than the thicker bedding. Bedding in shale may arise from the introduction of sandy laminae, or by changes in the texture

of the mud, earth, clay, etc., of which the shale was made. *Sandstones* are sometimes divided into beds by shaly or clayey partings, but quite as often by variations in the coarseness of the sand itself, or by the presence of laminæ or layers that are less coherent than those above and below. Sandstones may be thick or thin-bedded and their bedding passes insensibly into lamination.

Sand is usually deposited in relatively shallow water where it is subject to much shifting before it finds a permanent lodgment. In the course of this shifting, bars or reefs are formed which usually have a rather steep face in the direction in which they are being shifted. The sand carried over the top of the bar finds lodgment on the sloping face opposite. The inclined laminæ thus formed constitute a kind of bedding, but since its planes do not conform to the general horizontal attitude of the formations as a whole, it is called *false* or *cross-bedding*, or, more accurately, *cross-lamination* (Fig. 303). The same structure is developed on delta fronts, and generally in water shallow enough to be subject to frequent agitation at the bottom. Sandstone is cross-bedded more commonly than shale or limestone. The bedding of *conglomerate* is due chiefly to variations in coarseness, and laminæ or beds of sand often occur between the layers of coarser material. Conglomerate is often thick-bedded, and cross-bedding is common.

Lateral gradation. When the varying nature of the agitation of the sea at different depths and along the different parts of a coast is considered, it will be understood that deposits of one kind may grade into others horizontally. Thus a bed of conglomerate (gravel) may grade laterally into sandstone (sand), and this into shale (mud) or limestone. It is indeed more remarkable that sedimentary strata are as regular and persistent as they are, than that they sometimes grade into one another.

Special markings. The rhythmical action of waves gives rise to undulatory lodgment, known as *ripple-marks* (Fig. 263). They are usually not the direct product of the surface-waves, as shown by the fact that they are much smaller than these waves. They are sometimes made by streams and stream-like currents. Under proper circumstances, ripple-marks are preserved indefinitely. Ripple-marks are also made by wind (Fig. 61). They are usually

only a few inches from crest to crest, but in rare instances they attain much greater size, examples 30 feet across being known.¹ Occasional ridges and depressions of much greater dimensions are produced which are attributable to the formation of successive bars, or to the building of wave-cusps.² *Rill-marks* are not infrequently produced by the undertow and other currents passing over pebbles, shells, etc. (Fig. 264).

Sediments are sometimes exposed between tides, or under other circumstances, for periods long enough to permit drying and

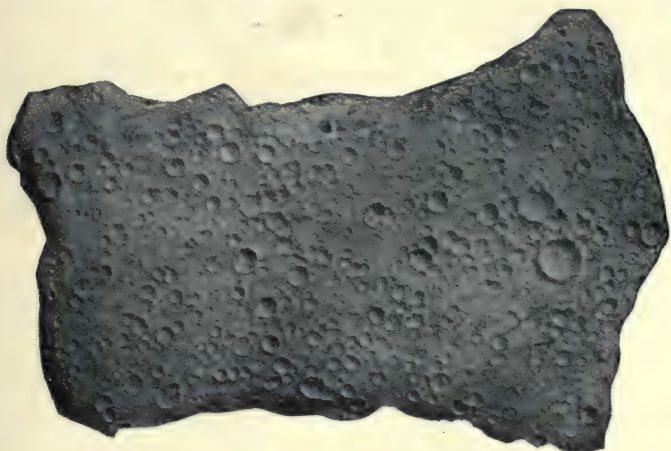


Fig. 304.— Raindrop impressions. (Brigham.)

cracking at the surface. On the return of the waters, the cracks may be filled and permanently preserved. These are known as *sun-cracks* or *mud-cracks* (Figs. 267 and 268). They affect shales chiefly, but are occasionally seen in limestones and fine-grained sandstones. During the exposure of the sediments, a shower may pass, and *raindrop impressions* (Fig. 304) be made which are subsequently filled by fine sediment and preserved.

Unconformities. In Figs. 305, 306, and 307, one set of bed is seen to be out of harmony with another set. This relation is one

¹ Gilbert, Bull. Geol. Soc. Am., Vol. X, 1898, pp. 135, 140.

² Branner, Jour. Geol., Vol. VIII, 1900, pp. 481-484.

of *unconformity*. An unconformity is developed by the erosion, the deformation, or both, of the older and lower set of beds before

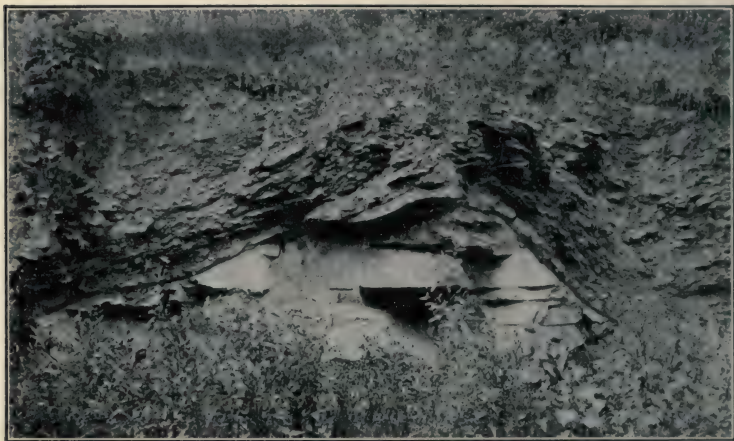


Fig. 305.—An unconformity between the Devonian (the thick-bedded rock) below, and the Coal Measures (thin-bedded and broken) above. The surface of the lower rock was eroded before the deposition of the upper part upon it. (Udden.)

the deposition of the younger and upper set. The interval of time between the deposition of the two unconformable sets of beds may be very long — when the unconformity is said to be great, or short

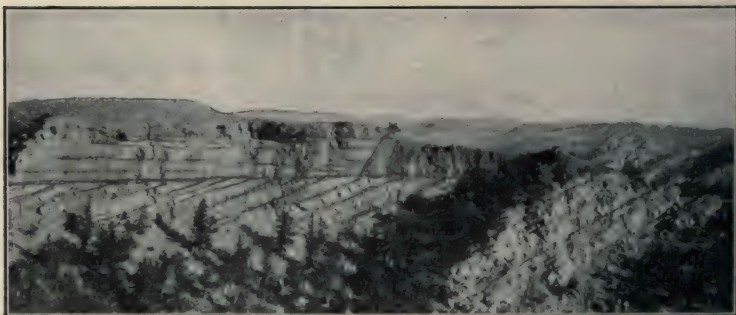


Fig. 306.—An unconformity in Bighorn Basin, Wyoming. The lower (Laramie) beds dip notably to the left, and the upper horizontal (Wasatch) strata rest upon the cut-off edges of the dipping beds. (Fisher, U. S. Geol. Surv.)

— when the unconformity may be slight. Unconformities are often of great significance in the interpretation of geological history.



Fig. 307.— One phase of unconformity. The beds at the right were tilted to their present position before the deposition of the beds at the left.

There may be unconformities between stratified rock and igneous rock, and between stratified rock and metamorphic rock, as well as between different series of bedded rocks.

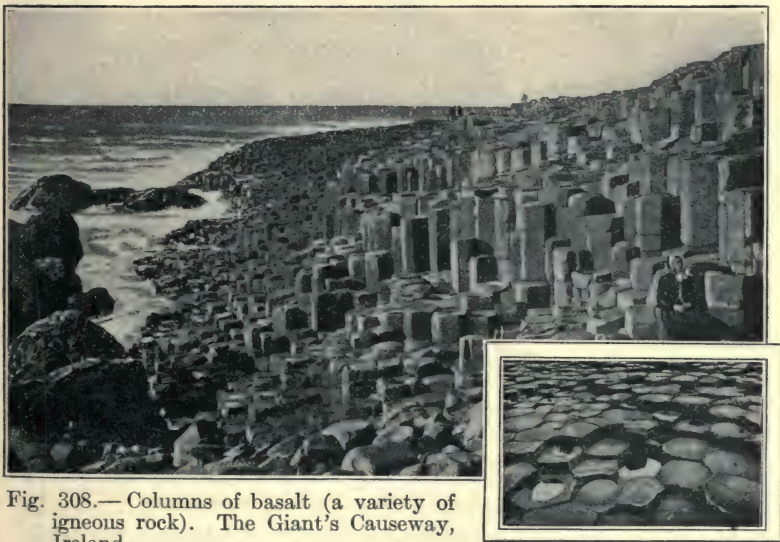


Fig. 308.— Columns of basalt (a variety of igneous rock). The Giant's Causeway, Ireland.

Igneous Rocks

Certain large structural features of igneous rocks have been mentioned in treating of their origin in the previous chapter. When a great flow of lava spreads out upon the surface, there is

no internal lamination or stratification, and the resulting rock is usually classified as massive rather than stratified; but when a succession of flows occurs, each individual flow forms a layer, and the series as a whole becomes stratiform. The successive flows are not usually co-extensive. If the later flows of the closing stages of a period of vulcanism fail to reach as far as the earlier ones, a terrace or step-like aspect is given to the region, whence the name *trap-rock* ((*trappe*, steps) is derived. Such lava sheets, especially if of basalt, often assume a *columnar* structure in cooling, the columns being rude six-sided prisms standing at right angles to the cooling surfaces (Figs. 8 and 308). This phenomenon is sometimes well developed in *sills* (p. 15). The formation of the columns is sometimes regarded as a variety of concretionary action, but more commonly as a result of contraction (p. 17). The various structural forms due to intrusions of lava have been enumerated (p. 367).

Metamorphic Rocks

The conspicuous structural feature of metamorphic rocks is their schistosity (p. 14). Crumpling has followed the development of the schistose structure in many cases. Slaty cleavage, which represents incipient metamorphism, has been referred to (p. 53), as have the causes which produce metamorphism.

Features Arising from Disturbance

Inclination and folding of strata. The original attitude of beds, whether formed by water or by lava-flows, commonly departs but little from horizontality. Both kinds of deposits, however, occasionally take place on considerable slopes. Modifications of the original attitude result from earth movements, and the measurement of these modifications is an important feature of field study. The position of beds is recorded in terms of *dip* and *strike*. The dip is the inclination of the beds referred to a horizontal plane, as illustrated in Fig. 309, and is usually measured by a clinometer, shown in Fig. 310. In measuring the dip, the maximum angle is always taken. The direction as well as the amount of the dip is to be noted. Thus dip 40°, S. 20° W., gives the full record of the position of the bed of rock under consideration. The strike is

the direction of the horizontal edge of dipping beds, or more generally, the direction of a horizontal line along the outcropping edge of a dipping bed, as illustrated in Fig. 309. Since the strike is always at right angles to the dip, the strike need not be recorded

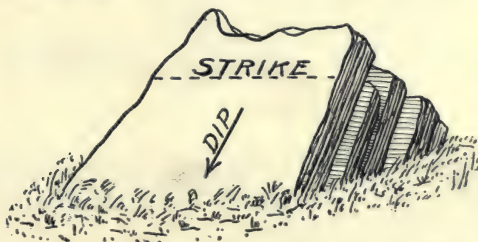


Fig. 309.— Diagram illustrating dip and strike. (J. Geikie.)

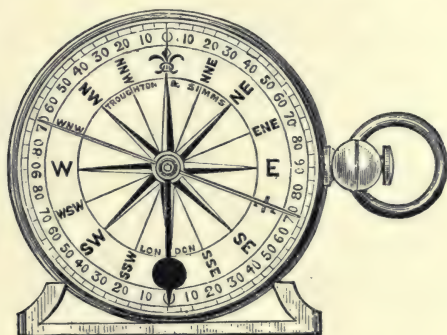


Fig. 310.— The compass and clinometer. The black bob at the bottom points to 0° . If the base of the clinometer were depressed at the right, the bob would swing over to 10° , 20° , 30° , etc.

if the direction of the dip is. Thus dip 40° , S. 20° W. is the same as dip 40° , strike N. 70° W.

When beds incline in a single direction, they form a *monocline*. When they are arched up as in a fold, they form an *anticline* (Figs. 16 and 17). The anticline may depart from its simple form, as shown in Fig. 311. The downfold corresponding to an anticline is a *syncline* (Fig. 312). When beds assume the position shown in Fig. 18, the folds are *isoclinal*. When considerable tracts are bent so as to form great arches or great troughs with many minor

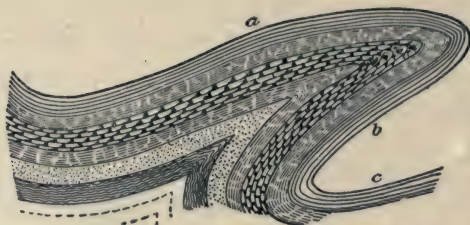


Fig. 311.— Recumbent anticline. (Van Hise, U. S. Geol. Surv.)



Fig. 312.— Syncline, C. and O. canal, 3 miles west of Hancock, Md. The beds are shale and sandstone, near base of the Silurian. (Walcott, U. S. Geol. Surv.)

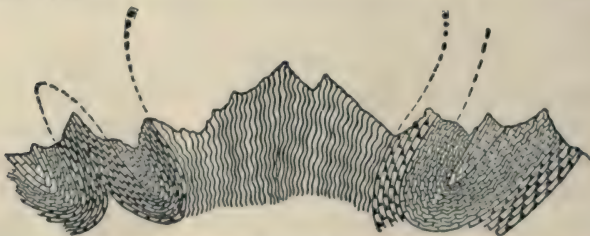


Fig. 313.— Generalized fan fold of the central massif of the Alps. (Heim.)

undulations on the flanks of the larger, they are called *geanticlines*, or *anticlinoria* (Figs. 286 and 313), and *geosynclines* or *synclinoria* (Fig. 314). Folding is often accompanied by the development of slaty cleavage (p. 53).

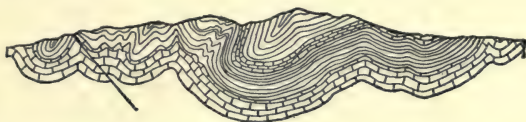


Fig. 314.—Synclinatorium, Mt. Greylock, Mass. (Dale, U. S. Geol. Surv.)

As found in the field, folds are usually much eroded, and often completely truncated (Fig. 313). The structure is then determined by a careful record of dips and strikes. On the field map, the record

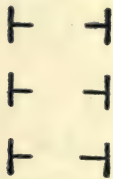


Fig. 315.



Fig. 316.

Fig. 315.— Map record of dip and strike, showing synclinal structure.

Fig. 316.— Diagram showing the structure corresponding with Fig. 315, as seen in cross-section.

may be made as shown in Figs. 315 and 317, where the free ends of the lines with but one free end, point in the direction of dip, while the other lines represent the directions of strike. Applying this

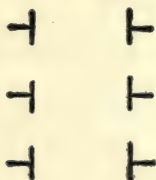


Fig. 317.



Fig. 318.

Fig. 317.— Map record of dip and strike showing anticlinal structure.

Fig. 318.— The structure of the area shown in Fig. 317, in cross-section.

method, the structure shown in Fig. 315 represents a syncline, and that in Fig. 317 an anticline. In cross-section, the structure presented by Fig. 315 would appear as in Fig. 316. Fig. 319 shows

a doubly plunging anticline; that is, an anticline the axis of which dips down at either end. Fig. 320 shows a combination of syn-

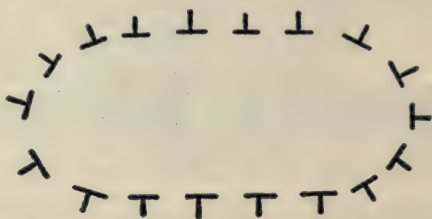


Fig. 319.— Map record of dip and strike showing plunging (dipping down at ends) anticline.

clines and anticlines, and Fig. 321 a cross-section along the line *ab* of Fig. 320. The outcrops of rock where the dip and strike can be

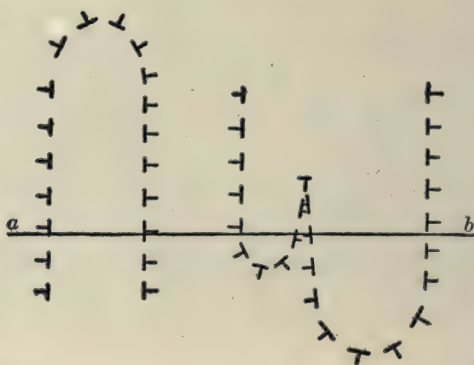


Fig. 320.— Map record of dip and strike showing complex structure.

determined may be few and far between, but when they are sufficiently near one another, the structure of the rock, as shown in Fig. 320, may be worked out, even though the surface is flat.



Fig. 321.— Cross-section of Fig. 320, along the line *ab*.

Much the larger portion of the earth's surface is occupied by beds that depart but little from their original horizontal attitude, but in mountainous regions the beds have usually suffered bending, folding, crumpling, and crushing, in various degrees, in the course of the deformations that gave rise to the mountains. Distortion

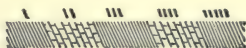


Fig. 322.—This diagram might represent either isoclinal or monoclinical structure. In the former case, the strata might have the structure shown in any one of the figures 323 to 325, so far as dip and strike show. (Dana.)

is on the whole most intense and characteristic in the most ancient rocks. Distortion is assigned chiefly to lateral thrust arising from the shrinkage of the earth, as explained in Chapter IX.

Complicated structures may be very difficult of interpretation. Thus overturned folds reverse the order of the strata in the under limb of the fold (Fig. 311). After such folds have been greatly

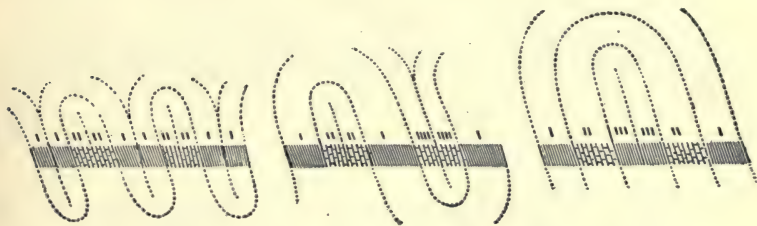


Fig. 323.

Fig. 324.

Fig. 325.

Fig. 323.—A possible interpretation of Fig. 322. (Dana.)

Fig. 324.—A possible interpretation of Fig. 322. (Dana.)

Fig. 325.—A possible interpretation of Fig. 322. (Dana.)

eroded, so that their outer form is lost and their relations have become obscure, the reversed beds are likely to be interpreted as though they lay in natural order. In such a case as that represented in Fig. 322, a complex structure may be interpreted as a simple one. Thus these strata may have the structure shown in Fig. 323, 324, or 325, so far as dip and strike show.

Joints. The surface rocks of the earth are almost universally traversed by deep cracks called *joints* (Figs. 2 and 327). In most regions there are at least two systems of joints, the crevices of each

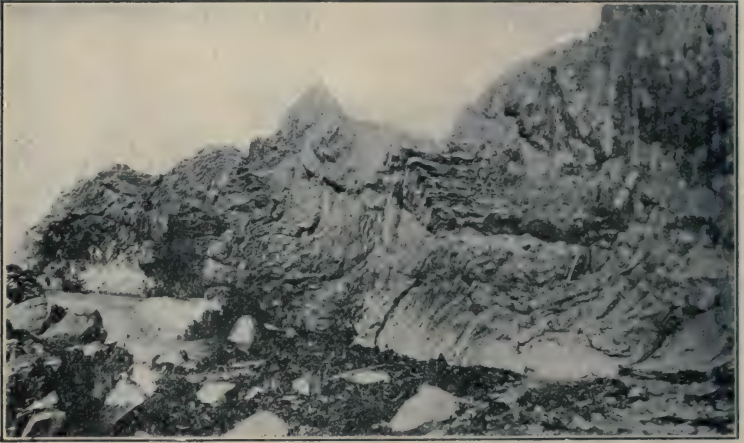


Fig. 326.—Contorted shales and greywacke. Ardwell, near Girvan, Ayrshire. (H. M. Geol. Surv.)

system being roughly parallel to one another, while those of the two systems, where there are two, are approximately at right angles. In regions of great disturbance, the number of sets of joints is often

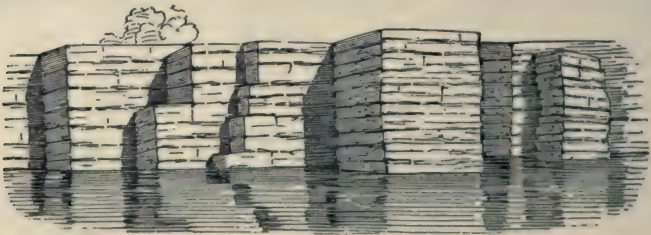


Fig. 327.—Jointed rocks. Cayuga Lake, N. Y. (Hall.)

three, four, or even more. The joints of each set may be many yards apart, or in exceptional cases, but a few inches, or even a fraction of one inch.

In undisturbed rocks the joints approach verticality, but in regions where the rocks have been notably deformed, the joint planes may have any position. In igneous and metamorphic rocks they may simulate bedding planes (Fig. 328). Joints do not ordinarily show themselves at the surface in regions where there is much mantle rock, but they are readily seen in the faces of cliffs, in quarries, and, in general, wherever rock is exposed. Though some of them extend to greater depths than rock has ever been



Fig. 328.— Tabular joints in granite. Summit of Goatfell, Arran. (H. M. Geol. Surv.)

penetrated, they are believed to be relatively superficial phenomena. They must be limited to the zone of fracture, and most of them are probably much more narrowly limited. Joints frequently end at the plane of contact of two sorts of rock. Thus a joint extending down through limestone may end where shale is reached. Joints are frequently offset at the contact of layers or formations, and a single joint sometimes gives place to many smaller ones. All these phenomena may be explained by the varying elasticity of various sorts of rock. Generally speaking, rigid rock is more readily jointed than that which is more yielding.

Joints may remain closed, or they may gape. They may be widened by solution, weathering, etc., and they may be filled,

partly or wholly, by detritus from above, or by mineral matter deposited from solution (veins). Many rich ore-veins are developed along joint-planes.

Joints have been referred to various causes, among which tension, torsion,¹ earthquakes,² and shearing³ are the most important. Most of them may probably be referred to the tension or



Fig. 329.— A surface of sandstone marked by numerous joints, chiefly in two rectangular sets. Near Kinghorn, Fife. (H. M. Geol. Surv.)

compression connected with crustal movements.⁴ In the formation of a simple fold, for example, tension-joints parallel with the fold will be developed if tension goes beyond the limit of elasticity of the rock involved. If the axis of a fold is not horizontal, that is,

¹ Daubree. *Geologie d'Experimentale*, Tome 1, pp. 306-372.

² Crosby. *American Geologist*, Vol. XII, 1893, pp. 368-375.

³ Becker. *Bull. U. S. Geol. Surv.*, Vol. X, pp. 41-75. *G. S. A.*, Vol. IV.

⁴ Van Hise. *Principles of North American Pre-Cambrian Geology*; 16th Ann. Rept., U. S. Geol. Surv., Pt. I, pp. 668-672.

if it "plunges," as it commonly does, a second set of tension-joints roughly perpendicular to the first may be developed. If the uplift is dome-shaped and sufficient to develop joints, they will radiate from the center. It is true that joints affect regions where the rocks have not been folded, and where they have been deformed but little, but deformation to some extent is well-nigh universal.

Shrinkage is a cause of certain minor tension-jointing. The columnar structure of certain lavas, and the cracks developed in mud when it dries, are examples. These causes, however, are not believed to affect rock structures to great depths.

Exceptionally, open joints are filled by the intrusion of sedimentary material from beneath. Thus have arisen the remarkable *sandstone dikes*¹ of the West, especially of California. Such dikes are sometimes several miles (nine at least) in length. The sand of these dikes was forced up from beneath either by earthquake movements or by hydrostatic pressure.

Faults.² The beds on one side of a joint-plane or fissure are sometimes elevated or depressed relative to those on the opposite side. Such a displacement is one type of a *fault* (Figs. 33 and 34). Joint-planes and fault-planes may vary from verticality to approximate horizontality. The angle by which the fault-plane departs from a vertical position is known as the *hade* (*bac*, Fig. 330). The vertical displacement (*ac*) is the *throw*, and the horizontal displacement (*bc*) the *heave*. The heave and the throw are to be distinguished from the *displacement*, which is the amount of movement along the fault-plane (*ab*, Fig. 330). The cliff above the edge of the downthrow side is a *fault-scarp*. In many, probably in most cases, the scarp has been destroyed, or at any rate greatly obscured by erosion; but occasional fault-scarps of mountainous heights are found, as along the east face of the Sierras and along many of the

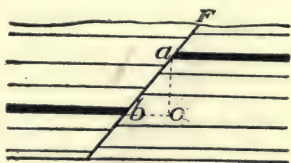


Fig. 330.— Diagram of a normal fault.

¹ Diller. Bull. Geol. Soc. Am., Vol., I, pp. 441–442. Ibid., Hay, Vol. III, pp. 50–55; and Newsom, *ibid.*, Vol. XIV, pp. 227–268.

² Chamberlin. Economic Geology, Vol. II, pp. 585 and 704.

basin ranges of Utah and Nevada. As a rule, they are much modified by erosion (Fig. 331).

The rock on either side of a fault-plane is often smoothed as the result of the friction of movement. Such surfaces are *slickensides*. A slickenside surface has some resemblance to a glaciated surface, but is generally more glazed.

Faults involving vertical displacement along joints are of two general classes, *normal* (or *gravity*) and *reversed* (or *thrust*). In



Fig. 331.— A fault-scarp, modified by erosion. The triangular faces rising abruptly above the plain at the ends of the spurs are remnants of the scarp. (Davis.)

the normal fault (Fig. 330) the overhanging side is the downthrow side, i. e., the downthrow is on the side towards which the fault-plane declines, as though the overhanging beds had slid down the slope. Normal faults, as a rule, indicate an extension of strata, this being necessary to permit the dis severed blocks to settle downwards. In the reversed fault (Fig. 34), the overhanging beds appear to have moved up the slope of the fault-plane, as though the displacement took place under lateral pressure. This is clearly

shown to be the case where an overfold passes into a reversed fault (Fig. 332). Another type of thrust-fault is shown in Fig. 333.

In thrust-faults, the heave is often great. The eastern face of the Rocky Mountains near the boundary-line between the United States and Canada has been pushed over the strata of the bordering

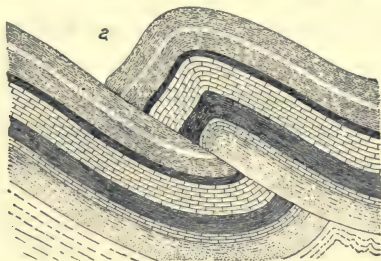


Fig. 332.—Diagram of a reversed or thrust fault. (U. S. Geol. Surv.)

plains to a distance of at least seven or eight miles.¹ Overthrusts of comparable displacement have been detected in Scotland,² and elsewhere.

Sometimes a fault branches, and sometimes the faulting is along

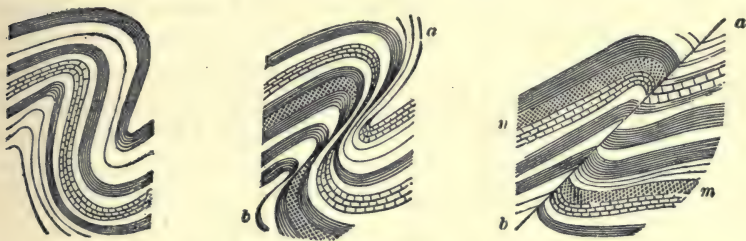


Fig. 333.—Diagrams showing relations of faults and folds.

a series of parallel planes near one another,³ instead of being along a single plane. Such a fault is *distributive* (Fig. 37).

Faults are found to die out when traced horizontally, sometimes

¹Willis, Bull. Geol. Soc. of Am., Vol. XIII, pp. 331-336, and McConnell, Canada Geol. and Nat. Hist. Surv., 1886, Pt. II.

²Geikie, Text-book of Geology.

³Becker, Geology of the Comstock Lode, Mono. III, U. S. Geol. Surv., Chapter IV.

by passing into monoclinal folds (Fig. 38), and sometimes without connection with folding. In depth they probably die out in similar ways in most cases. A fault of thousands, or even hundreds of feet is probably the sum of numerous slight slippings distributed through long intervals of time. The faulting along one plane may be the cause of many earthquakes.

The significance of normal and reversed faults.¹ Faults afford an indication of the conditions of stress and tension to which a region has been subjected, but some caution must be exercised in their interpretation. Normal faults usually indicate an extension of the surface sufficient to permit the fault-blocks to settle down unequally. Reversed faults usually signify a compression of the surface which required the blocks to overlap one another more than before the faulting. In other words, normal faulting usually implies tensional stress, and reversed faulting compressional stress. There may be cases of normal faulting in a region of compressed and folded strata, and reversed faults in regions of tension; but such cases are exceptional and usually local. These exceptional cases aside, the general inference from prevailing normal faults is that the regions where they occur have undergone stretching, while the inference from the less widely distributed thrust faults is that the surface where they occur has undergone compression.

In view of the current opinion that the crust of the earth has been subjected to great lateral thrust as a result of cooling, it is well to make especial note of the fact that the faults which imply *stretching* are called *normal* because they are the more abundant; and that the faults which imply thrust are less common, and are styled *reversed*. The testimony of normal faults in favor of tension is supported by the prevalence of gaping crevices, and of veins which are but crevices that stood open until filled by deposition. All these phenomena seem to testify to a *stretched* condition of the larger part of the surface of the continents.

Faulting may bring about numerous complications in the outcrop of rock formations, as already illustrated (pp. 65-67).

Faults of horizontal displacement. The preceding discussion has concerned faults which involve more or less vertical displace-

¹ Van Hise, Sixteenth Ann. Rept., U. S. Geol. Surv., Pt. I, pp. 672-678.

ment along joint planes, but faulting is not limited to such displacements. Horizontal displacements may take place along a joint plane, with no vertical displacement, and this also is faulting. Horizontal displacement often accompanies vertical displacement, and the former is as much a part of the faulting as the latter is. The tendency of recent study, whether based on theory or on field observation, is to emphasize the importance of the horizontal movement in faulting. In numerous mines, for example, where the walls of the shafts and tunnels afford excellent opportunity for determinations, horizontal movement is much more in evidence than vertical.

There are various displacements of rock bodies not mentioned above which are akin to faulting, if not to be regarded as such. Thus when strata are folded there is some slipping of layer on layer. Occasionally there is displacement of layer on layer, even when the beds are not folded. Such a case with a well developed "*slicken-side*" surface is known in Ohio, between beds which are nearly horizontal. The recognition of such movements as faults opens a wide door. The great variety of displacements along joints or other partings in the rock, shows the difficulty of defining faults sharply. Many movements of displacement, which can hardly be separated from faults logically, are not usually called faults.

Map work. The sections of the Structure Section Sheets of the folios of the United States Geological Survey furnish abundant illustrations of a variety of structural features, such as folding and faulting, and the relations of sedimentary, metamorphic, and igneous rocks. The sections of various Bulletins, Professional Papers, etc., of the same Survey afford other illustrations.

PART II

HISTORICAL GEOLOGY

CHAPTER XII

THE ORIGIN OF THE EARTH

The bedded rocks of the earth's shell reveal its history far back into the past with great fidelity; but the record of the still earlier ages is indistinct, and if an attempt be made to follow the history back to its beginning, the indistinctness merges into obscurity. The rocks below the well-bedded strata are so broken and altered, and so cut up by intrusions, that their history is read with the greatest difficulty. Still lower lies the inaccessible interior of the earth whose nature is more a matter of inference than of knowledge.

Some suggestions as to the origin of the earth may be found in its relations to the other bodies of the solar system, and certain features of the solar system give pointed hints as to its early history. The interpretation of these outside relations and of the secrets of the hidden interior is yet far from clear, and our only recourse at present is to hypotheses. It is nevertheless important that we should study, with due reserve, these hypotheses, and note with care the ways in which they enter into the interpretations of the earth's phenomena, for not a few of the leading doctrines of geology hang on some hypothesis of the earth's beginning, and have no greater strength than the hypothesis on which they depend.

HYPOTHESES OF THE EARTH'S ORIGIN

It is the nearly unanimous conviction of astronomers that the solar system was evolved in *some* way from a nebula of *some form*. Until recently, astronomers so generally accepted the view of La-

place that it came to be known as "The Nebular Hypothesis"; but the advance of inquiry makes it necessary now to consider other hypotheses which maintain that the solar system arose from a nebula, but a nebula whose constitution and mode of evolution differed from that postulated by Laplace. The leading hypotheses of the earth's origin may be grouped in three classes:

I. *The gaseous hypotheses*, in which the parent nebula is assumed to have been formed of gas collected into a spheroid by gravity in accordance with the laws of gases, and to have been evolved into the present solar system by loss of heat, and the separation of the outer parts into planets. The type of the class is the Laplacian hypothesis.

II. *The meteoritic hypotheses*, in which the parent nebula is assumed to have been a swarm of meteorites, the members of which moved in diverse directions, and suffered frequent collisions giving rise to heat, light, and vaporization. The swarm of meteorites is thought to have behaved essentially as a coarse gas, and the evolution of the system to have been dynamically like that of the gaseous system.

III. *The planetesimal hypothesis*, in which the original constituents are assumed to have been small bodies, molecules, or aggregates, moving in orbits about a common center and forming a disk-like system. The bodies are supposed to have been controlled by revolution about the center of the nebula, and not by impact on one another. The evolution consisted in the gathering of these small bodies, planetesimals, into planets and satellites. Dynamically, this hypothesis differs more from the other two than they do from one another.

I. *The Laplacian or "Nebular" Hypothesis*

During the last century the Laplacian hypothesis was very generally accepted, and geological theories as to the early states of the earth, and as to many later events in its history, were built upon it, and these views are still prevalent. The hypothesis is so well known that a few sentences will recall its essential features. It holds that the sun, the planets, and the satellites were once parts of a glowing, rotating, spheroidal, gaseous nebula, which was ex-

panded enough to embrace the whole space of the present system. The nebula was assumed to have cooled by radiation of heat, and in cooling to have shrunk. This shrinkage accelerated the rate of rotation, and this in turn increased the equatorial bulge which rotation developed. The progressive increase of cooling, rotation, and bulging finally led to the separation of an equatorial ring. As this ring also cooled and contracted, it was disrupted and its substance gathered into a planet whose orbit lay in the plane the ring had occupied. A series of rings, separated in this way, gave rise to the several planets in turn, while the central mass formed the sun. The orbit of any planet bounds approximately the space assigned to the nebula at the birth of that planet. At the time of their formation, the several planets were thought to be hot, gaseous, and rotating. Cooling and shrinkage increased the rate of their rotation, and this caused a bulging of their equatorial zones, till some of them, following the example of their parent body, shed rings which became satellites.

In support of this ingenious theory many harmonies in the motions of the members of the solar system were cited, and in the early days of the hypothesis, the phenomena of existing nebulae were thought to give it much support, for among them, as then known, there seemed to be nebulous aggregations in various stages of development, from diffuse nebulous patches on the one hand, to forms almost as concentrated as suns on the other. Critical students of celestial mechanics have always recognized difficulties in the hypothesis, but to those who did not follow the closer reasoning on which its truth or falsity must rest, the hypothesis seemed to afford a plausible starting point for the history of the solar system, and was accepted as if its foundations were firm. Without a knowledge of celestial mechanics and of the molecular activities of gases, it is scarcely possible to appreciate the full force of the arguments which bear against it, but some of them may be stated briefly.

1. In the evolution of a gaseous nebula, it is highly improbable that rings would be formed, for the molecular activities would cause the molecules to separate from the parent nebula one by one.
2. There are grave difficulties in the contraction of a ring

into a spheroid as simply and promptly as postulated by this theory.

3. In the highly heated condition assigned the earth-moon ring, its gravity could hardly have held the common gases together, because of their intense molecular activities. The earth, even now, does not appear to be able to hold permanently very light gases, though it does hold the heavier ones which have slower molecular velocities.

4. It is probable that the attenuated substance of a ring, such as the supposed earth-moon ring, would have cooled to solid particles long before it could collect into a spheroid, and hence no secondary ring to form a moon would be developed.

5. The inner satellite of Mars (Phobos) revolves about that planet three times while the planet rotates once. According to the Laplacian theory they must have rotated together at the time of separation, and the planet should have kept on increasing its rotation by cooling after the separation. Its period of rotation should therefore have been shorter than the period of the satellite's revolution. It has been suggested that the planet's rotation was lengthened by its tides, but so much lengthening is very unlikely. If accepted in this case, it is hard to apply it consistently to the similar anomaly of the small bodies that make up the inner edge of the inner ring of Saturn, and they revolve in about half the time of that planet's rotation.

6. If the solar system were converted into a gaseous spheroid, and so expanded as to reach out to Neptune's orbit, and had its matter distributed according to the laws of gases, and if this nebula were endowed with the total value of the momentum (technically the moment of momentum) now possessed by the solar system, it would not have had a rate of rotation rapid enough to detach matter from its equator at that stage, or at any later stage *until it had contracted well within the orbit of the innermost planet.*

7. If the expanded spheroid were given the rates of rotation necessary to shed rings at the proper stages (if rings could be formed), the moment of momentum at each stage must have equalled that of the matter it then contained; for the total moment of momentum of any such system must remain constant so far as its

own evolution is concerned. Now computations show that at the stage which marked the birth of Neptune, according to this hypothesis, the moment of momentum of the nebula must have been more than 200 times as great as the present moment of momentum of the solar system; that at the stage of Jupiter's formation, the moment of momentum must have been 140 times too great; that at the Earth stage, it must have been 1,800 times too great; and so on. Here is not only an enormous discrepancy, but one that varies greatly and irregularly from stage to stage.

8. If the masses of the planets are compared with the moments of momenta they carried off from the parent nebula, strange discrepancies are disclosed. The matter in the ring supposed to have formed Jupiter and his moons had a mass less than one-thousandth of that of the nebula at the time of its separation; but Jupiter and his moons now have about 95 per cent of the total moment of momentum which the nebula then had. The Laplacian hypothesis thus calls on us to believe that an equatorial ring having a mass less than a thousandth of the mass of the parent body, carried off in its separation 95 per cent of the total moment of momentum. The supposed separation of other rings involves similar incredible ratios.

9. Under the Laplacian hypothesis, the satellites should all revolve about their planets in the direction in which the planets rotate on their axes; but the recently discovered ninth satellite of Saturn revolves in the opposite direction.

10. Though our knowledge of nebulae has been extended greatly in recent years, nebulae with such rings as the Laplacian theory postulates have not been found. The larger number of those at first supposed to support the theory have been found by improved methods of research to be spiral nebulae or anomalous forms.

II. *The Meteoritic Hypotheses*

It was long ago noted that shooting stars entered the upper atmosphere nightly in great numbers, and that occasionally fragments of stony and metallic matter fall from the heavens. Out of this grew the notion that the earth may have been built up in this way, save that the process was more rapid in the early ages of the

Earth's building. This notion, however simple and natural, may be dismissed without serious consideration, for the diverse directions of motion and the various velocities of meteorites are such as to forbid the belief that a system of such symmetrical discoidal form and of such harmonious motions as the solar system presents, could have been formed in this manner.

The hypothesis of Lockyer and Darwin. A meteoritic hypothesis of more logical character has been based on the conception that meteorites may be aggregated into swarms and constitute nebulae. This hypothesis is, therefore, nebulo-meteoritic. Inquiry into the mechanical possibilities of the case led Sir George Darwin to the conclusion that such a swarm of meteorites would act very much like a gas, and that the laws of gases may be applied in determining its mechanical properties. So far as it applies to the origin of the earth, this form of the meteoritic hypothesis is thus found to be practically identical with the gaseous hypothesis, and so far as it applies to the dynamics of the solar system, it is subject to the criticisms already urged against that hypothesis. It is to be noted that these criticisms apply only to such meteoroidal nebulae as may be formed of swarms of meteorites the members of which move in diverse directions, and frequently collide with one another. If the meteorites were assembled so as to pursue concentric orbits and form a disk-like system, they would be controlled by planetoidal or planetesimal dynamics, and fall into the following class. The term meteoritic hypothesis is here used essentially as employed by Lockyer and Darwin, and should be carefully distinguished from the planetesimal hypothesis, whose mode of evolution is radically different. The meteoritic hypothesis as thus defined is applied by its authors chiefly to the earlier and more scattered states of the nebulae, and has not been specifically applied to the formation of a planet, perhaps because a meteoritic nebula tends to pass into a gaseous nebula as it condenses.

III. *The Planetesimal Hypothesis*

When the shortcomings of the Laplacian hypothesis came to be so clear and cogent that there was no apparent way of escape from them, an alternative better in accord with the facts was sought.

It had been held that the matter of a nebula, if formed of particles revolving independently about their common center of gravity, could not be gathered into planets without giving these a backward rotation, at least normally; but the six inner planets have forward rotations. All hypotheses of the planetesimal type appeared,

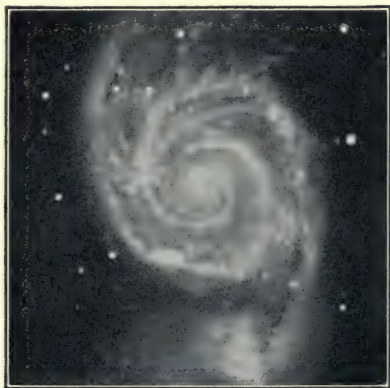


Fig. 334.— A spiral nebula in Canes Venatici, Messier 51. The exposure was long and has given relative exaggeration to the fainter parts. The nucleus is apparently dense and relatively massive; the coiling is pronounced and rather symmetrical in the inner parts, but departs from symmetry in the outer parts. A second nucleus is attached to the extremity of one arm. If this be interpreted as the representation of the disturbing star, it should perhaps be regarded as made of colder, heavier material, much less subject to expulsive elasticity, and hence less dispersed, and only slightly affected by rotating influences. A notable feature is the comet-like streamers of some of the knots and denser portions. If these are true streamers, curved by motion, they imply an active rotation, and strengthen the similar inference drawn from the coiled condition. The system is perhaps to be interpreted as young, but as having advanced rapidly in its rotatory evolution because of its massive nucleus. (Photo. by Ritchey, Yerkes Observatory.)

therefore, to be shut out; but closer analysis showed that the earlier conclusion was an error and thus a field, previously supposed to be closed, was opened. It has also been shown by astronomic photography that there are a multitude of nebulae,—at least ten times as many as were known a few years ago,—and that in this multitude, there is one dominant form, the spiral nebula (Fig. 334). This form has a central nucleus, from which two arms or sets of arms

start forth on opposite sides and curve spirally outward. The arms often branch, and are much interrupted and knotted, and between them there is much scattered hazy matter; but even in the more diffuse forms, the presence of two arms is discernible. The prevalence of this form of nebula implies that it is due to some process which is pervasive. The numerous nebulous knots on the arms, and sometimes more or less outside them, are significant

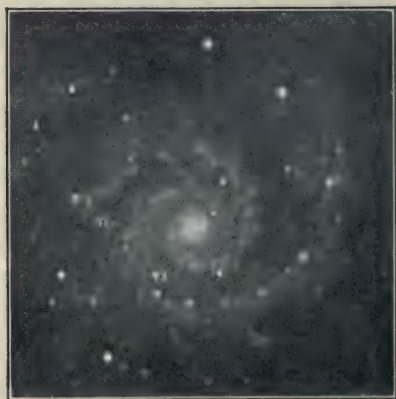


Fig. 335.—A typical spiral nebula in Piscium, Messier 74, with very symmetrical arms, pronounced nucleus and knots, and a relatively limited amount of nebulous haze. (Photo. from Lick Observatory.)

features. Clearly the matter has a very unequal dispersal and does not conform to the symmetric laws of gaseous distribution.

Recent advances in spectroscopy throw much light on the constitution of nebulae. As just inferred from their forms, the spiral nebulae seem to be composed, not of gaseous molecules, but of solid or liquid particles. These tiny bodies are believed to revolve about the center of the nebula, like little planets, but this has not yet been proved. If it were positively known that the particles of the spiral nebulae revolve about the centers of the nebula in elliptical orbits like planets, and were thus planetesimals, these nebulae might well be called *planetesimal nebulae*. The planetesimal hypothesis is based on a spiral nebula of this supposed organization.¹

¹The manner in which it may have arisen is discussed in the authors' larger work on Geology, Vol. II.

For the building up of the solar system, the planetesimal hypothesis starts with a spiral nebula consisting of the following elements: (1) the main knots to serve as nuclei for the planets, (2) small

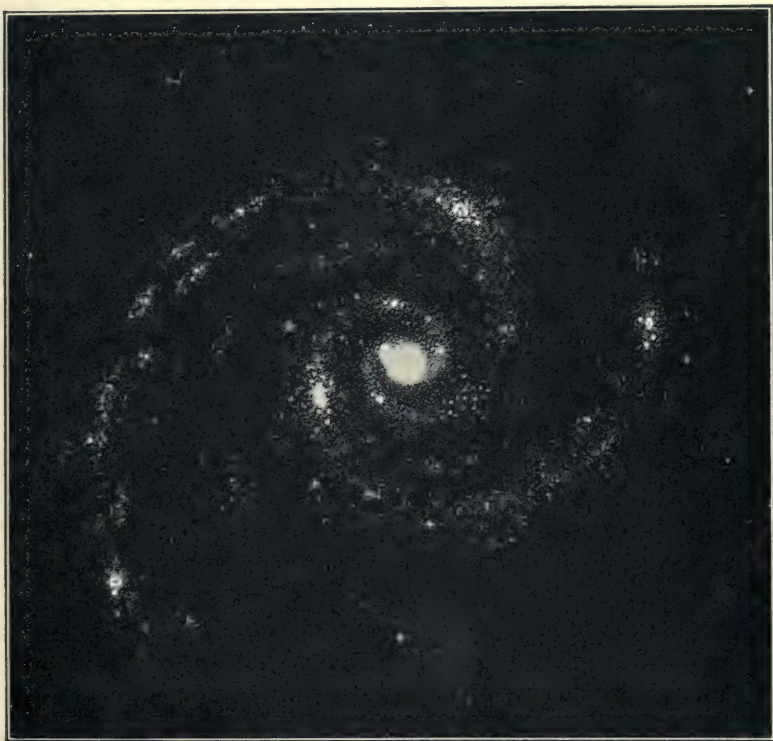


Fig. 336.— Theoretical restoration of the parent nebula of the solar system. The nuclei of the several planets may be identified by their distances from the center. The dimensions of the inner parts are made disproportionately large.

scattered knots as the nuclei of the asteroids, (3) other small knots near to the large knots and controlled by them, as the nuclei of the satellites, and (4) scattered matter or nebulous haze to be gathered into these nuclei to give them their mature sizes, and (5) the great central mass of the nebula, forming the nucleus of the sun. The gathering of the scattered planetesimals into the knots to form

the planets, planetoids, and satellites, is assigned to the coming together of these bodies as they pursued their slightly different orbits, not as the result of falling directly together under the control of gravity. It is assumed that the planetesimals had rather highly elliptical orbits arranged in disk-like form, and such orbits would be favorable for the conjunction of the bodies following them. It can be shown mathematically that under such conditions the addition of planetesimals to the nuclei would give them more and more circular orbits as the accessions took place, and it is significant that the planetoids (asteroids), which presumably have grown little, usually have the most eccentric orbits, that Mercury and Mars, the smallest of the planets, have the next most eccentric orbits, while the orbits of the larger planets approach circularity most closely. The photographs of spiral nebulae show large knots with small ones near them, which appear quite susceptible of evolution into planets attended by satellites. They also show small scattered knots susceptible of forming planetoids. The earth-moon system is assumed to have been derived from companion nuclei of very unequal sizes.

The knots might have had a rotary motion at the outset, arising from inequalities of projection at the time of their formation; but, in the main, the rotations of the planets are assigned to the impacts of the planetesimals as they joined the nuclei to form the planets, and this would naturally give rise to notable inequalities. There would be no fixed relation between the rotation of a planet and the revolution of its satellites; the period of the latter might be either longer or shorter than that of the former. Even if the revolution-period of a satellite-nucleus was originally the same as the rotation-period of the planetary-nucleus, the growth of the planet might draw the satellite nearer to itself and shorten the time of its revolution, and thus the difficulty of Phobos and of the innermost particles of the ring of Saturn be obviated. The mode of accretion thus assigned might give rise to forward rotation, or to retrograde rotation of the planets and satellites; the forward rotation should be the rule, and retrograde rotation the exception, as is actually the case. In a spiral nebula, formed in the way assigned, the outer parts of the arms should be composed of lighter materials

than the inner parts, and since the planets were formed from these arms, the inner ones should have higher specific gravities than the outer ones, as is the fact.

Other peculiarities of the solar system seem to find a fitting explanation in the planetesimal hypothesis, but most of these must be passed without mention here.

The meetings and unions of planetesimals and nuclei at the crossings of their orbits imply a relatively slow evolution of the nebula into a solar system, however inevitable the evolution must be with the requisite time. The planetesimal hypothesis therefore implies a relatively slow growth of the earth. With such a mode of growth, the stages of the earth's early history necessarily depart widely from those postulated by the Laplacian and the meteoritic hypotheses.

CHAPTER XIII

STAGES OF THE EARTH'S HISTORY LEADING TO THE KNOWN ERAS

The conception of the development of the earth prior to the earliest stage at which its history can be read directly from the strata must depend upon the view which is entertained as to its origin. The course of its early history, according to each hypothesis of its origin, may be followed separately. These possible courses are necessarily hypothetical at present, and should not be entertained without due reserve; yet their study is important, for the great features of the earth and of the earth-shaping processes were inherited from these early stages.

I. STAGES UNDER THE LAPLACIAN HYPOTHESIS

The hypothetical stages of the earth's early history, according to the Laplacian view have been stated as follows:¹

- I. The *Astral æon*, or that of the fluid globe having a heavy vaporous envelope containing the future water of the globe or its dissociated elements, and other heavy vapors or gases.
- II. The *Azoic æon*. Without life.
 1. The *Lithic Era*: Commencing with the earth a solid globe, or at least solid at the surface; the temperature at the beginning above 2,500° F.; the atmosphere still containing all the water of the globe (amounting to 200 atmospheres, according to Mallet, 1880), all the carbonic acid now in limestone and that corresponding to the carbon now in carbonaceous substances and organic substances (probably 50 atmospheres), all the oxygen since shut up in the rocks by oxidation, as well as that of the atmosphere and of organic tissues. The time when lateral pressure for crustal disturbance and orographic work was begun; when "statical metamorphism," or that dependent on heat of a statical source — the earth's mass and the vapors about it, — began.

¹ Dana, *Manual of Geology*.

2. The *Oceanic Era*: Commencing with the waters condensed into an ocean over the earth, or in an oceanic depression, with finally some emerging lands,— the temperature perhaps about 500° F., if the atmospheric pressure was still 50 atmospheres. The first of tides and the beginning of the retardation of the earth's rotation. Oceanic waves and currents and embryo rivers begin work about the emerged and emerging lands; the large excess of carbonic acid and oxygen in the air and water a source of rock-destruction; before the close of the era, the formation of limestones and iron-carbonate by chemical methods, removing carbonic acid from the air and so commencing its purification; the accumulation of sediments without immediate crystallization or metamorphism, and thereby the beginning of the earth's *supercrust*.
- III. The *Archæozoic æon*. Life in its lowest forms in existence.
1. *The Era of the First Plants*: Algæ, and later of aquatic Fungi (Bacteria), commencing with the mean temperature of the ocean at possibly 150° F., since plants *now* live in waters up to and even above 180° F. Limestones formed from vegetable secretions, and silica deposits from silica secretions; iron-carbonate, and perhaps iron-oxides formed through the aid of the carbonic acid of the atmosphere and water; large sedimentary accumulation, where conditions favored, thickening the *supercrust*.
 2. *The Era of the First Animal Life*: Mean temperature at the beginning probably about 115° F., and at the end 90° F., or lower; limestones and silica deposits formed from animal secretions; deposits of iron-carbonate and iron-oxides continued; large sedimentary accumulations.

Quite apart from any doubt as to the mode of genesis, two serious questions relative to the processes outlined in this sketch have arisen from recent investigations, the one growing out of the failure to find any great basal formation having the distinctive characteristics of an original crust; and the other from doubt as to the possibility of so prodigious an atmosphere as that postulated.

1. *Relative to an Original Crust*

The theory of a molten earth carries the presumption that the liquid mass arranged itself concentrically, with the heaviest matter at the center and the lightest on the outside. As the granitoids are the lightest of the large classes of igneous rocks, the granitoid magmas should have formed the outer zone of the molten earth, and should have been spread out homogeneously according to their

specific gravity. The solid crust should have been similarly light and homogeneous, and it should have formed a universal stratum susceptible of identification. Except at the very surface, it should have been completely crystallized, for the cooling must have been very slow, a condition favorable for the growth of crystals. No very large amount of fragmental volcanic material can be assumed to have covered the original crust if we entertain the view that the primitive atmosphere contained all the water of the future hydrosphere, for that leaves no adequate explosive agency in the molten globe to produce abundant volcanic fragments. Such material cannot well be supposed to have concealed the original crust permanently, for many thousands of feet of rock have been eroded from the surface of the oldest known areas. It is equally improbable that the original crust has been concealed *everywhere* beneath sediments derived from itself. There should therefore be areas of the original crust exposed at the surface and they should presumably be large.

Until recently, the great granitoid areas of the Archean system (the oldest known rocks) were thought to answer these obvious characteristics of an original crust; but it has been found that most of these great granitoid masses are *intrusive* in rocks which had previously been formed *on an older surface* by (1) lava outflows, (2) volcanic explosions, and (3) sedimentation. This reduces to an unknown, and apparently to a vanishing quantity, the rocks that can be referred plausibly to a supposed original crust. If the trend of further investigation shall follow the present tendency and finally exclude all the accessible rocks from an original crust, the molten theory will have lost its observational support, at least in its original form.

2. *Relative to the Primitive Atmosphere*

The primitive atmosphere has usually been held heretofore to have been vast, hot, and heavy, and to have contained (1) all the water of the globe, (2) all the carbon dioxide now in carbonated rocks, (3) that portion of the oxygen which has been added to the rocks by oxidation, as well as (4) that portion of all these constituents which is now found in the atmosphere and in organic tissues.

The assumption back of this seems to be that heat always promotes the expulsion of gases; if so, the separation of the gases from the rock should have been most complete in the white-hot primitive globe. This conception has been widely entertained, and the reverse conception that the cooled rocks re-absorb the atmospheric constituents is expressed in the once prevalent view that the former atmosphere and hydrosphere of the moon have been absorbed into that body, and the familiar prophecies of a similar doom for the atmosphere and hydrosphere of the earth.

Adverse physical evidence. So great an atmosphere with so much carbon dioxide and water-vapor should have given the earth a warm and equable climate. Such climates indeed seem to have prevailed at certain times during the earlier parts of the earth's history, as also during the later; but the studies of the past two decades have shown that there was extensive glaciation *on the very borders of the tropics*, as early as the close of the Paleozoic, and that there was glaciation in northwestern Europe, in China in Lat. 31° , in Australia, and perhaps in South Africa, as far back as the very beginning of the Paleozoic. Less striking, but perhaps not less significant, is the occurrence of extensive beds of salt and gypsum in the early Paleozoic, in rather high latitudes. These deposits seem to imply severe and protracted aridity, not readily reconcilable with an enormous, equalizing atmosphere.

There seem to have been, in Paleozoic times, much the same alternations of very uniform with very diversified climates that marked the Mesozoic and Cenozoic eras. In other words, changes of climate seem to have been much the same in early as in late geologic time.

Adverse organic evidence. The more the early life is compared with modern life, the more nearly does it appear to imply the same atmospheric conditions, and the more insecure does any view become which postulates conditions profoundly different from those of to-day. The air-breathing animals which lived early in the Paleozoic era, and the xerophytic (indicating aridity) organs of plants that lived in the later part of that era, seem irreconcilable with a vast, hot, vaporous atmosphere, overcharged with carbon dioxide and water-vapor.

The hypothesis of an enormous original atmosphere, suffering gradual depletion, finds, therefore, scant support in a critical study of either the biological or the physical history of the earth.

II. POSSIBLE MODIFICATION OF THE PRECEDING VIEW

The most troublesome phases of the preceding scheme arise from the assumption that the lighter gases were excluded from the hot molten globe, and so formed a vast atmosphere. If it is possible to amend the hypothesis, it must be done, apparently, by assuming that the earth held large quantities of gaseous constituents throughout the molten stage, and discharged them later. Since lavas now bring to the surface great volumes of absorbed gases, it is not, on its face, inconsistent to suppose that a globe of molten rock might contain large quantities of the atmospheric gases. It is perhaps admissible to assume further that some notable part of the atmospheric material remained in the rock after its solidification, since igneous rocks now contain notable quantities of gas. By making these assumptions, the primitive atmosphere may be held to have been less extensive than in the preceding view, and gaseous material may be supposed to have been held in reserve in the earth-body to actuate future vulcanism and to feed the atmosphere and hydrosphere.

This modified view makes it possible to suppose that the formation of the crust may have been followed by a period of exceptional volcanic activity, during which the primitive shell was buried so deeply under volcanic matter that it has not since been exposed by erosion. It is consistent then to suppose that the oldest rocks accessible are these volcanic products, mingled with such sedimentary material as was formed contemporaneously with them. In this way the hypothesis may be made to fit the earliest rocks now known, fairly well. It is not clear, however, that the physical assumption on which it is based is sound, for experimental evidence seems to indicate that highly heated rock material discharges its gases, rather than retains them.

The modified hypothesis is only partially successful in meeting the atmospheric difficulties, for there must have been added to the

primitive atmosphere the accessions of the great volcanic period, and these together would probably have given a gaseous envelope not altogether unlike that of the preceding view, though less excessive.

The modified hypothesis furnishes a somewhat better basis than the older view for the volcanic activity of later periods, and for a supply of gases to the atmosphere to offset the loss due to chemical combination of its constituents with the surface rocks; but it is not clear that it is adequate.

Stages under the Modified Hypothesis

The stages of evolution under this view may be summarized as follows:

1. **The astral eon.** The separation of the material of the earth from the parent nebula and its aggregation into a rotating gaseous spheroid.

2. **The molten eon.** The condensation of the rock matter of the gaseous spheroid into a molten spheroid surrounded by a hot vaporous atmosphere, the molten spheroid retaining occluded within itself some notable part of the water of the present hydrosphere, as well as much of the carbon dioxide represented by the present carbonates and carbonaceous deposits.

3. **The lithic eon.** The solidification of the molten spheroid, beginning perhaps at the center, on account of pressure.

4. **The primitive volcanic eon.** Prodigious volcanic action, closely following the solidification of the crust, during which great beds of lava were poured out on the surface, followed by great intrusions of other lavas into and through them. Contemporaneous with this volcanic action, the atmosphere and hydrosphere gave rise to some sedimentary deposits, which were interbedded with the volcanic products, but were greatly inferior to them in volume. This period would correspond to the Archeozoic eon.

5. **The sedimentary eon.** The remaining time up to the present has been characterized by the dominance of the atmospheric and the hydrospheric activities over the volcanic, and the result is recorded in the common sorts of sedimentary rocks. This eon

began with the deposition of the proterozoic sedimentaries, and continues to the present.

III. STAGES OF GROWTH UNDER THE PLANETESIMAL HYPOTHESIS

It is possible to suppose that the earth grew up by accessions in some other mode than that of planetesimal evolution, but the latter furnishes the basis for the following sketch of probable stages:

(1) **The nuclear stage**, which started with the nebular knot and proceeded by its gradual condensation as planetesimals were gathered into it, until it became a small planet which continued to grow by the capture of more planetesimals. No specific mass is assigned to the nuclear knot save that its mass was sufficient to control its constituents.

(2) **The initial atmospheric stage.** There may have been a stage after the nucleus was condensed during which the earth was too small to hold the gases of an atmosphere, but if the earth then had a mass one-tenth or more of its present mass, it probably had a limited atmosphere like that of Mars; if it was much smaller than this, it probably had little or no atmosphere. Whatever the atmospheric state at the start, it is assumed that as the earth grew, atmospheric molecules were gathered to it, and sooner or later it gained the power to hold them, and accumulate an atmosphere. Gaseous molecules should have come in from without, the same as other planetesimals, and gases should have been given forth from the rock material that went to form the growing earth, particularly after volcanic action had set in. The heavier gases should have been retained at an earlier stage, while the lighter ones came under control later.

Gases or gas-producing material was no doubt contained in the original planetesimals, since gases are given forth from nearly all rocks and meteorites to-day when heated in a vacuum,¹ and as the planetesimals were aggregated and heated, a part of their gaseous material should have escaped and become a part of the atmosphere. Because the presence of these gases and gas-producing materials in rocks is so general, it is thought probable that many

¹ The Gases in Rocks, R. T. Chamberlin, Carnegie Institution, 1908.

of the gases now issuing from volcanoes are a part of what was held in the original planetesimals, and that they are now reaching the atmosphere for the first time.

(3) **The initial volcanic stage.** Before the earth grew to any large part of its present mass, the self-compression which arose from its own gravity is thought to have produced sufficient internal heat to have reached the melting points of the common kinds of rock under low pressures, and as this heat crept outward, it would reach rocks at pressures that would permit liquefaction. Recent discoveries have led to the belief that heat arising from radio-activity has also been an agency in developing high internal temperatures, and in thus promoting volcanic action. It is not known how the initial stages of the atmosphere and of vulcanism were related to one another in order of time, but later they ran parallel with one another, and volcanic action is believed to have made notable contributions of gas to the atmosphere.

(4) **The initial hydrospheric stage.** Water in the form of gas is light and active, and may at first have escaped; but when the earth had attained sufficient size, water vapor was held in the atmosphere, and when at length the point of saturation was reached, it took the liquid form and initiated the hydrosphere. The source of the water, according to the hypothesis, was the same as that of the atmospheric gases.

It may be added here that the hypothesis gives a simple explanation of the ocean basins and continental protuberances. It is obvious that, because of unequal growth, the surface of the earth might never have been perfectly spheroidal, so that when the accumulation of water upon its surface began, it gathered into the depressions. The planetesimal material which afterwards fell into the water was protected from weathering, while the material that fell on the protuberant areas was exposed to weathering, with its attendant lessening of specific gravity. Thus the depressed areas tended toward higher specific gravities, and hence toward still further depression when deforming stresses were brought to bear on them, while the elevated areas tended to grow relatively lighter, and to suffer relative elevation, under the stress of deformative movements. Thus the differentiation of the oceanic basins from

the continental protuberances began almost as soon as the hydrosphere began to gather, which was long before the earth had reached its present size, and has continued to the present time.

(5) **The initial life stage.** Suitable conditions for life did not exist until after some notable development of the atmosphere and the hydrosphere, but as these were gathered about the earth at an early stage, it is possible that some forms of life began long before the earth was full-grown. Under the planetesimal hypothesis, therefore, the time during which life may have existed on the earth is very much longer than the time assumed under the older hypotheses.

(6) **The climax of volcanic action.** While volcanic action may have begun soon after the beginning of the earth's growth, it probably had to await (1) sufficient growth to give the requisite heat by compression, and (2) sufficient time for the heat so developed to creep out to zones of less pressure, where it would suffice to liquefy the more fusible (soluble) parts of the rock. Vulcanism was probably hastened by radioactivity. Once begun, it is believed to have gradually increased in importance, and only reached its climax some time after the more rapid growth of the earth had ceased.

For obvious reasons, the climax of vulcanism was attended by deformations of exceptional intensity. The transfer of so much material from below to the surface required readjustment within, and the intrusion of the enormous granitic batholiths, such as are found in the early formations, was in itself a cause of deformation. Diastrophism probably had its climax with the climax of vulcanism, and both came, by hypothesis, about the time of the opening chapter of the well-recorded history of the earth.

The formations of the period when volcanic action was at its height, including some contemporaneous sedimentary deposits, are regarded as constituting the oldest accessible rocks of the earth (the Archean Complex), though probably only the later part of the great volcanic series is represented by the *known* Archean. It is for each student to judge whether the assigned antecedents lead felicitously or otherwise into the actual state of things which the oldest known rocks reveal. The value of a hypothesis, when its

truth cannot be at once demonstrated, lies mainly in its working qualities.

(7) **The gradational stage.** To complete the survey of stages, it is necessary to note that after the growth of the earth had ceased and volcanic action had passed its climax, the surface was no longer subject to continual burial, but was exposed, age after age, to the action of air and water. The material removed by these agents from the higher parts was deposited in the basins. Throughout all this remaining period, the dominant geologic processes were therefore gradational. Vulcanism and diastrophism continued to be important, but not dominant. This stage embraces the Proterozoic and later eras.

Synoptical View of the Earth's History

The stages of the earth's history fall into two great groups, with a transition period between. The first group includes *the stages of growth* and the last *the stages of maturity*. In tabular form, and numbered in chronologic order, these stages appear as follows:

III. The Gradational Eon (Relative maturity)	10. The Cenozoic era	The better known eras
	9. The Mesozoic era	
	8. The Paleozoic era	
	7. The Proterozoic era	
II. The Extrusive Eon (Transitional)	6. The Archeozoic era	The partially known eras
	(Under planetesimal hypothesis)	
	5. The initial life stage	The hypothetical eras
	4. The initial hydro-spheric stage	
	3. The initial volcanic stage	
	2. The initial atmospheric stage	
I. The Formative Eon (Birth and adolescence)	1. The nuclear or nebular stage	
	(Under gaseous hypothesis)	

CHAPTER XIV

THE ARCHEOZOIC ERA

The sketches of the early stages of the earth's history presented in the last chapter are no more than inferential, yet they afford a helpful introduction to the study of that part of the earth's history which is recorded in the rocks. Figs. 337-339 represent diagrammatic radial sections illustrative of the different conceptions of the constitution of the earth's interior. The following summary should make the figures clear:

1. According to the conception of the history of the earth based on the Laplacian or gaseo-molten hypothesis, there should be pre-sedimentary igneous or meta-igneous rock at all points below the prevailing sedimentary rocks of the surface (Fig. 342). The plane of demarkation between these two sorts of rock should, as a rule, be distinct.

2. According to the suggested modification of the gaseo-molten hypothesis (p. 430), the above distinction would fail; for between the original crust and the sedimentary rocks above, there should be a zone composed of mingled igneous and sedimentary rocks, or their metamorphic equivalents (Fig. 338). This intermediate zone might not be sharply differentiated either from the original crust below or the sedimentary group above.

3. According to the planetesimal theory, (1) the core of the earth (Fig. 339) is made up of nebular or planetesimal matter. After aggregation, the planetesimal matter was probably recrystallized under the influence of the heat and pressure which the aggregation involved, the resulting rock being essentially igneous in its nature. Outside the central core there should be (2) a thick zone made up largely of planetesimal matter, but partly of igneous rocks erupted from below, and partly of sedimentary rocks. The planetesimal matter is assumed to predominate in the lower and

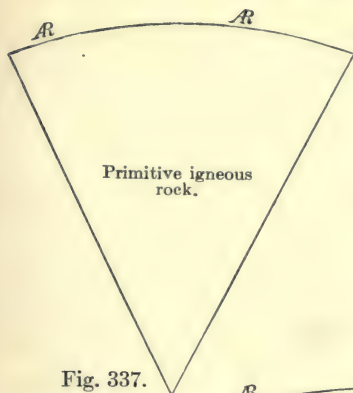


Fig. 337.

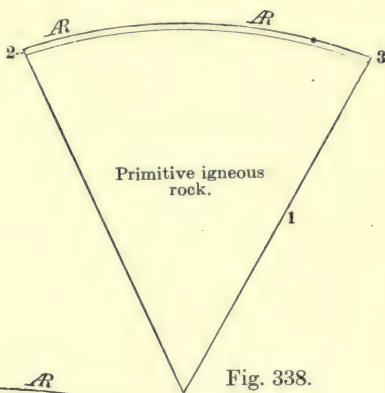


Fig. 338.

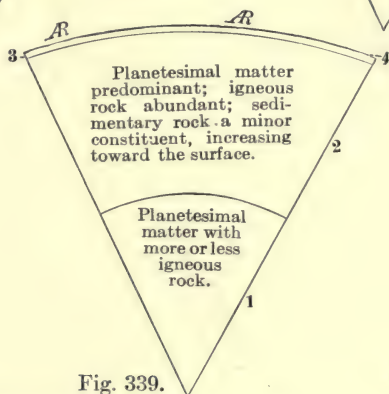


Fig. 339.

Fig. 337.— A diagrammatic sector of the earth illustrating its structure according to the Laplacian hypothesis. The great body of the earth is made up of the original igneous rock. Sedimentary rocks, together with some extrusive rocks, make but a thin coating, represented in the diagram by black, outside the great igneous interior. The original igneous rock is represented as appearing at the surface in some places (*R*). This, according to one view, might represent the Archean rock.

Fig. 338.— Diagrammatic sector of the earth illustrating its composition on the modified form of the Laplacian hypothesis. As in the preceding figure, the great body of the earth is made up of the original igneous rock. Outside this original igneous mass, there is, according to this hypothesis, a zone of extrusive material, with perhaps some sedimentary rock intermingled. This is represented by zone 2 in the diagram. The material of this zone is represented as coming to the surface at two points (*R*). Outside this zone, there is a third zone made up primarily of sedimentary, but subordinately, of extrusive rocks. According to one interpretation, the material of the second zone might constitute the Archean rock.

Fig. 339.— Diagram representing the structure of the earth according to the planetesimal hypothesis. The material of zones 1 and 2 is indicated in the diagram. Zone 3 of this figure corresponds to zone 2 of Fig. 338, and zone 4 of this figure corresponds to zone 3 of Fig. 338.

major part of this zone. Igneous rock, eruptive and irruptive, is assumed to have a somewhat irregular distribution through it, while sedimentary rock increases in importance above, but remains throughout a subordinate constituent. This zone records the growth of the earth from the initiation of volcanic and atmospheric processes to the close of the period of notable growth by accretion. The central core and this thick zone about it represent the Formative Eon (p. 435). (3) The next zone, relatively thin, is assumed to be made up largely of extrusive igneous rocks, with subordinate amounts of sediment and matter gathered in from space. This zone represents the Extrusive Eon (p. 435). (4) On the outside lies the superficial zone in which sedimentary rocks predominate, though associated with not a little rock of igneous origin. The first two zones outside the core are assumed to be universal, while the outermost one fails to completely cover the globe.

Conjectures concerning the oldest accessible rocks. With these theoretical sections in mind, it is pertinent to inquire what might be the nature of the oldest rock formations accessible, on the various hypotheses which the diagrams represent. The deepest excavations yet made in the earth are but little more than a mile in depth, and while, by reason of deformation and erosion, rocks once at greater depths have been exposed, the maximum thickness of rocks open to observation is but a few miles. Definite knowledge of rock formations and structures is therefore limited to some such thickness.

(1). According to the gaseo-molten hypothesis in its simple form, we might hope to reach the original crust; for it is not rational to suppose that the original crust, the principal source whence sedimentary rocks were derived, is everywhere covered so deeply by the material derived from it as to be inaccessible. (2). According to the modified form of the gaseo-molten theory, the oldest accessible rock should be the zone of mingled extrusive and sedimentary rocks between the original crust and the dominantly sedimentary formations above. (3). On the planetesimal hypothesis, the oldest rocks to which we might hope to gain access would be those referred to the Extrusive Eon (p. 435), during which more or less sedimentary rock was mingled with the volcanic. On

this hypothesis, as on the preceding, no sharp line of demarkation would be expected between dominantly sedimentary rocks above, and dominantly non-sedimentary rocks below.

The oldest rocks known. The rock-formations now most widely exposed at the surface are sedimentary, and were formed during the great Gradational Eon (p. 435). In not a few places, however, diverse formations which are predominantly extrusive (igneous or meta-igneous) are found, either beneath the prevailing sedimentary rocks, or projecting up through them in such relations as to show their greater age. In many cases these lower and older rocks were thoroughly metamorphosed, and in essentially their present condition, before the deposition of the overlying beds. These dominantly igneous and meta-igneous formations which antedate the oldest known series of dominantly sedimentary rocks are the oldest formations known, and the era during which they were formed is the first era of which there is definite record in the accessible formations of the earth.

This lowest and oldest group of rocks is very complex, embracing lava flows, volcanic tuffs, igneous intrusions of various types, and sedimentary rocks, all more or less metamorphosed and deformed. Distinct fossils have not been found in them, but the presence locally of (1) carbonaceous slates similar to younger slates which derived their carbon from organic sources, and (2) occasional formations of limestone and chert which, as a class, are usually the products of organisms, are thought to imply the existence of life, and to warrant placing the era when these rocks were formed in the zoic group (p. 435). The era during which or during the later part of which, this oldest system of accessible rocks was made, is the *Archeozoic* era.

Under the planetesimal hypothesis, the oldest known rocks may be confidently referred to the Archeozoic era, for, according to this hypothesis, rocks of organic origin and rocks containing organic products were not only mingled with all series that are accessible, but with a deep series below, since life is supposed to have originated long before the earth acquired its present size. The oldest formations known may also be *archeozoic* under the modified phase of the molten hypothesis which has been presented (p. 430);

but under the simpler form of the hypothesis of a molten earth, the original crust cannot be called *archeozoic*, since it antedated life. The term *Archean* (Archean System, Archean Complex) is often applied to the formations here referred to the Archeozoic era. This term is applied to the oldest group of accessible rocks, whatever their origin, and whether contemporaneous with life or antedating it.

Delimitations. The lower limit of the Archean system is assumed to be inaccessible. Its *upper limit* has been differently fixed by different authors. The term Archean (very old) was originally introduced to displace the older terms *Azoic* (without life) and *Eozoic* (dawn-life), whose etymological meanings made them no longer appropriate for the rocks to which they were applied. As first defined the Archean included all rocks below the Cambrian (p. 476); but progressive study has shown that there are several great systems of sedimentary or meta-sedimentary rocks (with much igneous rock), unconformable with one another, between the Cambrian system above and the Archeozoic system below. The systems of pre-Cambrian rocks which are dominantly sedimentary, should be separated from the dominantly igneous or meta-igneous complex below, and the term Archean is now generally restricted to the latter. The upper limit of the Archean is therefore the base of the oldest dominantly sedimentary system.

*General Characteristics of the Archean*¹

As now understood, the Archean is made up of two great classes of formations: viz., (1) a great schist series, and (2) a great granitoid series.

¹ Bull. 86, U. S. Geol. Surv., pp. 478-484, and 16th Ann. Rept., U. S. Geol. Surv., Pt. II, pp. 747-756. The interpretation of the Archean as set forth in these publications needs some modification in the light of recent discoveries. The sedimentary character of parts of the system is set forth in the following: Mono. XLV, U. S. Geol. Surv., pp. 129, 172-212; 21st Ann. Rept., U. S. Geol. Surv., pp. 317 and 402-404; Mono. XXVIII, U. S. Geol. Surv., pp. 186-188; Am. Geol., Vol. XXVIII, 1901, pp. 14-19; Jour. Geol., Vol. X, p. 71; Rept. of Bureau of Mines of Ontario, 1902, pp. 155-162; Geol. Surv. of Canada, Vol. III, Pt. I, F, 1887-99; Am. Jour. Sci., Vol. 50 (1895), pp. 58-69. Trans. Roy. Soc. Canada, 1899 and 1901. In the references to Canadian localities, some of the rocks classed as Archean (U. S.) are described under the name of Lower Huronian.

(1) **The schist series** is made up chiefly of the metamorphosed products of lava flows and volcanic tuffs. In composition these schists vary greatly; but the dominant types are hornblende schists, greenstone schists, mica schists, etc. Associated with the metamorphosed surface lavas and pyroclastic formations, there are some massive igneous rocks and occasional beds of metamorphosed conglomerate, sandstone, shale and limestone, and beds of iron ore, all of which imply the contemporaneous activity of water. In a few places, as at Vermilion, Minn., the iron ore is in workable quantities.

(2) Among the most conspicuous features of the Archean rocks, in their present eroded condition, are the great masses of *granite* and *gneiss* that protrude through the schists. Until recently, these granites and gneisses were commonly regarded as the oldest known rocks, and were styled "primitive" or "fundamental"; but it is now known that many of them, at least, are intrusions into the schist series, and therefore younger than the latter. The gneisses are regarded as metamorphosed granites.

In the formation of both the surface flows and the intrusions, the ascending lavas must have occupied numerous fissures or conduits connected with the interior, and hence there came to be numerous dikes and other intrusions, traversing the older parts of the Archean. It is also to be borne in mind that all younger intrusions and extrusions of lava must have passed through the Archean, leaving dikes and other bodies of igneous rock in it. These later intrusions are of course not strictly a part of the Archean system, but they are not always separable, and their presence adds to the complexity of the Archean as a whole.

Diastrophism and metamorphism. The most satisfactory explanation of the prevalent foliated structure of the Archean (Fig. 340) seems to be that which refers it to the movements of the outer part of the earth, in Archeozoic and later time. Intrusions of igneous rock probably helped to metamorphose the rocks by furnishing heat and by developing pressure in the zone where they were intruded. Not only this, but the transfer of so much material from below developed lateral pressure by causing the outer parts to settle down to take the place of the lava transferred upward.

The result would be lateral thrust in the outer parts of the earth, and this thrust would be relieved by the bending and crumpling of the rocks, and by shear.

That the rocks should have undergone extraordinary metamorphism under these conditions is natural. It has been demonstrated that massive igneous rocks, by crushing and shearing, have



Fig. 340.— Metamorphic rock, showing foliation distinctly; bank of the Ottawa River. (Ells.)

been transformed into rocks with a foliated or schistose structure, and it is in the rocks of this era especially that metamorphism of this type is found. It is now believed that the larger part of existing gneisses, as well as a considerable part of existing schists, acquired their foliated structure in this way; but it is to be understood that some of the schists and perhaps some of the gneisses arose from clastic formations by other processes of transformation. It is not to be understood that the metamorphism of the Archean rocks was completed during the Archean era. All metamorphosing processes of subsequent times have affected them.

It would indeed be difficult to obtain an exaggerated idea of the complexity of the rock which has caused this system to be called the "Archean Complex," the "Basement Complex," the "Fundamental Complex," etc. The rocks of no later era are so generally and so notably deformed, or so generally and so highly metamorphic. Because of these complications, the interpretation of these rocks is difficult, and such views of their classification and correlation as are now entertained are to be held subject to emendation as knowledge advances.

DISTRIBUTION AND LOCAL DEVELOPMENT

General distribution. The Archean is the one accessible rock system which, theoretically, completely envelopes the globe. No later system does this, for wherever the Archean comes to the surface, later formations are absent.

In speaking of the distribution of a formation, its distribution *at the surface* is generally meant, and in speaking of its surface distribution, the mantle rock (glacial drift, etc.) which overlies and conceals it is usually ignored unless it is so thick as to make the underlying formation indeterminable. When the surface distribution of the formation is given, therefore, it is not to be understood that the formation is literally at the surface everywhere within the area specified, but rather that it is exposed here and there within that area, and that between the points of exposure it is the uppermost formation beneath the mantle rock. In this sense, the Archean rocks are estimated to appear at the surface over about one-fifth of the area of the land; but since great areas in some continents have only been reconnoitered geologically, this figure is only a rough estimate.

In North America,¹ by far the largest area of Archean rock

¹ The literature on the Archean (as well as Algonkian [Proterozoic]) of North America was summarized by Van Hise in Bull. 86, U. S. Geol. Surv., in 1892. This publication gives full bibliography to its date. A later (1896) and briefer summary of the same subjects by the same author was published, Pt. II, 16th Ann. Rept., U. S. Geol. Surv., pp. 744-843. The pre-Cambrian literature since 1892 has been summarized from time to time by the same author, and by Leith, in the Jour. of Geol., as follows: Vol. I, pp. 304 and 532; II, pp. 109 and 444; III, pp. 227 and 709; IV, pp. 362 and 744; VI, pp. 527, 739, and 840; VII, pp. 190, 406, 702, and 790; VIII, p. 512; IX, pp. 79 and 441; and XII, pp. 63 and 161.

lies in Canada (Fig. 341), but it is to be noted that formations of the Proterozoic and later eras occupy numerous small tracts within the area shown on the map, though the Archean underlies them at no great depth. Lying rudely parallel to the great Canadian area on the southeast is an interrupted series of probable Archean tracts, extending from Newfoundland to Alabama. Similarly, on the southwest, there is a belt of detached areas stretching from Mexico to Alaska. In few places within these belts have the ancient rocks been studied in great detail. Lesser areas of Archean rock appear in Michigan and Wisconsin, in Minnesota, and in the Adirondack region of New York. In some of these regions, Archeozoic rocks have not been carefully separated from Proterozoic.

Detailed work has covered but a small part of this great tract of Archean rock. The vicinity of Lake Superior in Canada, Michigan, Wisconsin, and Minnesota, the area north of Lake Huron, and the Ottawa region in Ontario, are the areas where the system is best known.

Summary. By way of summary it may be said that the Archean system consists in some places of rocks which are mainly massive (igneous intrusions); in other places, of rocks which are mainly gneissic (chiefly meta-igneous); and in still others, of rocks (largely meta-igneous and subordinately meta-sedimentary) in which a schistose structure predominates. Furthermore, the rocks of each of these structural types have a wide range in composition, from acid on the one hand to basic on the other. Rocks of all these classes are often intimately associated, and any one may predominate over the others. In some places the rocks of the several structural types graduate into one another so completely as to leave no line of separation, while in others their definition is sharp. Thus massive rock sometimes appears in distinct dikes in the gneisses and schists, while schists are frequently in dike-like sheets in rocks which are more massive. Furthermore, the relations of these several sorts of rock have been enormously complicated by the distortion to which they have been subject. The structure and relations of the several sorts of rock in the system indicate that it was (1) by successive intrusions, large and small, of rocks of different chemical composition into (2) still older rocks which were originally (a)



Fig. 341.—The white areas north of Mexico represent exposures of Archean; the white areas south of the United States represent lack of knowledge; the black areas represent exposures of Proterozoic, while the lined areas represent Archean or Proterozoic, beneath later formations. The light shading about the borders of the land represents the area of the continental platform covered by sea-water, or what is the same thing, the area of the epicontinental sea for this continent.

chiefly extrusive-igneous and of varying chemical composition, but (b) subordinately sedimentary; and (3) by successive dynamic movements resulting in various degrees of metamorphism and deformation of the various parts, that the intricate structure and composition of the Archean complex was attained.

Though the variations in the rocks of the Archean system are great, there is, nevertheless, a certain homogeneity in the heterogeneity of the whole. No one considerable part of the system is very different from any other considerable part, and no definite and orderly relationship between the different parts has been made out over any considerable area. There appears to be no traceable succession of beds, and no definite stratigraphic sequence, such as can be made out in great series of meta-sedimentary rocks, however much folded and metamorphosed.

The Archean in other countries. The general characters and relations of the Archean in North America seem to be duplicated in other continents. Corresponding systems of rocks, made up primarily of meta-igneous rocks, but subordinately of meta-sedimentary rocks inextricably involved with them, are known in all continents. The general characteristics and relations of the Archean, as developed in North America, therefore appear to be essentially world-wide.

Bearing of the Archean on the theory of the origin of the earth. With the essential facts concerning the constitution and structure of the system in mind, it is in order to inquire to what hypothesis of the earth's origin they best adjust themselves. The constitution of the system makes it clear that it does not represent the original crust of the earth or its downward extension. It cannot be affirmed, however, that no part of what is now classed as Archean is referable to the original crust; that is, it cannot be affirmed that no part of the igneous or meta-igneous rock of the Archean is referable to an azoic or prezoic period, strong as the evidence against such reference may seem. On the other hand, all the facts now known concerning the Archean adjust themselves to the planetesimal hypothesis, or to the modified form of the gaseo-molten hypothesis. They cannot, however, be said to establish either, or to preclude other hypotheses of the origin of the earth.

The question of the origin of the Archean must, therefore, still be regarded as an open one.

Earlier views concerning the Archean. In explanation of the Archean system, many different hypotheses have been suggested at one time and another, most of them starting with the Laplacian hypothesis as a beginning. One of them is that the Archean rocks are wholly of metamorphosed sediments; a second, that they are igneous rocks produced by the fusion of sediments; and a third, that they are igneous rocks intruded beneath the oldest known sedimentary rocks after the deposition of the latter. These hypotheses have a historic interest, but since they are not now generally held by geologists, their consideration will be omitted.¹

Life during the Archeozoic era. The presence of carbonaceous material, of bedded iron ores that were once carbonates, of cherts, and of limestones, implies the presence of life during the era occupied in the formation of the Archean rocks. Since no fossils have been found, nothing is positively known of the character of the life, and little, except by inference, of its abundance.

Duration of the Archeozoic era. Of the duration of the Archeozoic era nothing can be said beyond the general statement that it was very great, a conclusion which is independent of any particular conception of the earth's origin. If the planetesimal hypothesis is the true one, there is no readily assignable lower limit to the Archeozoic system, and the duration of the Archeozoic era may exceed that of all subsequent time.

Climate. Of the climate of the era nothing is known except that it seems to have been such as to permit the existence of life, and the ordinary phases of sedimentation.

¹ See the authors' *Earth History*, Vol. II.

CHAPTER XV

THE PROTEROZOIC ERA¹

FORMATIONS AND PHYSICAL HISTORY

The time between the Archeozoic era and the deposition of the oldest system of rocks containing abundant fossils (the Cambrian) constitutes the Proterozoic era. It was the era when sedimentation first became the leading process in the formation of the geological record. During the era several great systems of sedimentary formations, unconformable with one another, were formed. With these sedimentary formations there is much igneous rock, some of which was intruded as sills and bosses, and some of which was extruded.

The Proterozoic rocks include the first great series of sedimentary strata which imply mature weathering, and the prolonged and continuous deposition, on low lands or in the sea, of weathered material derived from the adjacent lands. It is important to emphasize the inauguration of the dominance of these processes, for they have been the most conspicuous ones ever since. Taken as a whole, the era was marked by more igneous activity than any later one, and may therefore be regarded as a transition-time from the profoundly igneous era that preceded, to the markedly sedimentary eras that followed.

Stratigraphic relations of the Proterozoic rocks. Great unconformities separate the Proterozoic formations from the Archean below and from the Paleozoic above. Great unconformities usually involve three elements: First, a change in the attitude of the lower formation, as the result of which it is subject to erosion; second, a long period of erosion during which its surface is much

¹ Proterozoic, as here used, is a synonym for *Algonkian* as used by the U. S. Geol. Surv.

degraded; and third, another change resulting in the deposition of the upper series on the eroded surface (Figs. 305 to 307).

A sequence of events which might have given rise to the unconformable relations of the Archean and the Proterozoic, where seen, is illustrated by Figs. 342 and 343. Fig. 342 represents an area of land composed of Archean rock in such a position as to suffer erosion. The sediments derived from it are washed down to the



Fig. 342.—Diagram showing Archean land (*AR*) with sedimentation, *a*, along its borders. The coarser sediments are being deposited near the shore; the finer, farther from it. (Compare Fig. 343.)

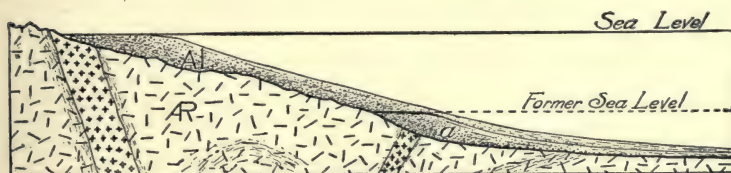


Fig. 343.—Diagram representing the same region as Fig. 342, after subsidence. The *a* of this figure corresponds to *a* of Fig. 342. It is to be noted that fine sediments overlie the coarse sediments deposited at an earlier time in the right-hand part of the figure.

sea and deposited in its waters (*a*). In Fig. 343, the land of the preceding figure is represented as having sunk so as to be partially submerged. A part of the sediments washed down from the remaining land are being deposited unconformably on the surface which has suffered erosion. The sediments *a* are older than the sediments *Al*, though the latter may be the oldest now accessible.

Great lapses of time were doubtless involved in the development of the unconformity between the Archean and the Proterozoic formations, but of this interval there is little more than conjectural knowledge.

Though unconformity between the Archean and the Proterozoic is wide-spread, it is presumably not universal. There were probably places, even on the land-areas, where the surface of the Archean did not suffer notable erosion before the deposition of Proterozoic sediments upon it, and there were quite certainly such places in the areas continuously covered by the sea.

Subdivisions. No classification of the Proterozoic formations has general application, but in the Lake Superior region, where these rocks are best known, four great unconformable systems are referred to this era. In some other regions the number is three

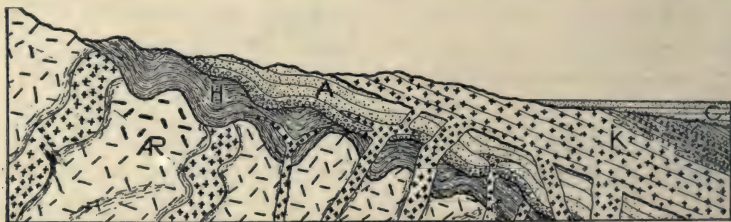


Fig. 344.—Diagram showing Proterozoic where it is composed of three systems of rock in the Lake Superior region. *H*, Huronian; *A*, Animikiean; *K*, Keweenawan. The diagram also shows the relation of these Proterozoic systems to the Archean (*A*) below and to the Cambrian (*C*) above. The cross-pattern represents igneous rock. The lines, dots, etc., above the Archean represent sedimentary beds.

(Fig. 344), in others two and in still others but one. In most places each system is thousands of feet in thickness, but, in spite of this, they do not constitute a complete record of the era. The unconformities between them show that, after the formation of each, there was a disturbance of relations between the sources of the sediments (the lands) and the sites of their deposition (chiefly the sea). Each unconformity appears to mark a prolonged period of erosion in the region where the formations are exposed, and deposition somewhere else. The only record of these periods is the unconformities themselves.

Proterozoic sedimentation. The surface of the Archean on which the Proterozoic sediments were deposited was probably comparable to existing land surfaces of crystalline rock which have been long exposed to weathering and other phases of erosion. The

topography was doubtless more or less uneven, and the surface mantled by soil and residual earths (mantle rock) which had arisen from the decay of the underlying rock. Large and small masses of rock, more resistant than their surroundings, probably remained undecayed, or but partially decayed, in the earths which represented the products of more complete decomposition.

The general nature of the clastic sediments laid down on such a surface when it became an area of deposition may be readily inferred. They were made up chiefly of (1) the disintegrated products already on the surface, (2) the materials worn from the rocks by the waves, if the surface was covered by the sea, and (3) river detritus.

(1) One of the first effects of the Proterozoic seas, as they slowly transgressed the land — for it is presumed that this transgression was slow — was to work over, assort, and re-deposit the loose material found on the surface. The larger masses of rock suffered little transportation and wear, the sand and small bits of rock were rolled along the bottom and deposited in relatively shallow water, while the fine materials were carried out from the shore and deposited in the more quiet waters beyond. Deposits of gravel, sand, and mud were doubtless being made at the same time at different distances from the shore, and from the gravel on the one hand, to the finest mud on the other, there were all possible gradations. Changes in the position of the shore line, and changes in the depth of water incident to the sinking of the land or the sea bottom, brought about the deposition of fine sediment on coarse, and of coarse sediment on fine. Thus the sedimentary deposits came to be arranged in beds of different sorts, coarser and finer alternating in vertical section, and grading into each other laterally.

As the land of Archean rock was submerged by the Proterozoic seas, the coarse materials of the mantle rock were left upon the surface in many places, with little movement and little wear. At the base of the Proterozoic there is therefore often a wide-spread deposit of coarse material (gravel, etc.) derived from the underlying rock (Fig. 345). Such a formation is known as a *basal conglomerate*, and is often one of the best indices of an unconformity.

If the climatic conditions were like those of the present, the

residual materials which the advancing Proterozoic seas found upon the surface which they transgressed had arisen chiefly by rock decay, and the material arising from the decomposition of the Archean was unlike the formation from which it came.

(2) Besides working over the decayed rock, the waves doubtless attacked the solid rock wherever exposures were favorable, just as waves here and there cut into solid rock at the present time. The materials thus derived resembled the parent formation in average composition, and are thus distinguished from those of the preceding

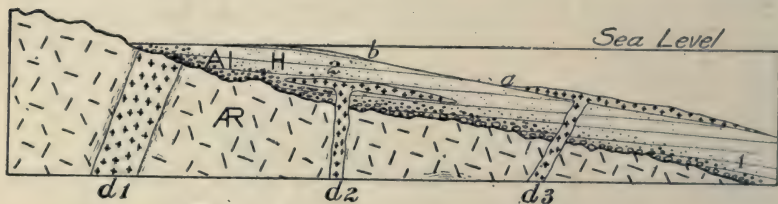


Fig. 345.—Diagrammatic section showing relations which existed around Archean lands during the Huronian period. Huronian sediments (*Al*) are in process of deposition. They are affected by intrusions of lava, *d*₂, *d*₃, etc.

class. The sediments of this second class were more or less intimately mingled with those which had been prepared in advance by the decomposition of the rock.

(3) The streams descending from the land must have brought down gravel, sand, and mud. The larger part of the river-borne detritus was probably made up of the decomposed products of rock, though a smaller part was doubtless derived by the mechanical action of running water on undecayed rock. Once in the sea, the river detritus was mingled with the sediments acquired in other ways.

Since some of the more soluble constituents of the Archean rock extracted during the processes of decomposition probably remained in solution in the sea-water, it is to be presumed that the clastic sediments were, on the whole, more silicious than the rock from which they were derived.

The sorting power of moving water takes account of the physical conditions and properties of the material handled, and not of

their chemical constitution; but in the decomposition of Archean rock, the quartz remaining in the residual mantle was generally in larger particles than the aluminous products of the decomposition of the silicates, and under the sorting influence of the waves the quartz grains (sand) were more or less completely separated from the aluminous particles (mud). Thus materials which were unlike chemically were separated from one another because they were unlike physically. If the Proterozoic seas had abundant life which secreted calcium carbonate, or if their waters anywhere became overcharged with lime carbonate, limestone might have been formed.

Extent. While the sediments accumulated in the Proterozoic era are known in limited areas only, it is to be borne in mind that Proterozoic sediments were in reality more wide-spread than the seas of the time; for though coarse material from the land is not usually washed out far from the shore, material fine enough to be carried in suspension may be transported great distances, and small amounts of dust are constantly being blown from the land to all parts of the sea. In later geologic time, the life of the sea has occasioned considerable deposits even far from the land, and presumably over the whole of the ocean bottom. The same may have been true from the beginning of the Proterozoic era, for the beginnings of life go even farther back. From extra-terrestrial sources, and by precipitation from solution, further additions may have been made to the sediments accumulating on the sea bottom. Sedimentation, even if slow, was therefore doubtless in progress everywhere in the Proterozoic seas, and on some parts of the land as well.

The exposed formations. The sedimentary beds of the Proterozoic consist of conglomerates, sandstones, shales, and limestones, or of their metamorphic equivalents. Before being cemented or otherwise solidified into firm rock, their materials were gravel, sand, mud, etc. The manner in which such materials are derived from older formations and transported to places of deposition, has been explained.

Basal conglomerate is of rather common occurrence at the base of the several systems of the Proterozoic, while the overlying beds

are of finer sediments. It is thought that the gravel of the conglomerates was accumulated along ancient shores, and that as the shores advanced upon the land, finer off-shore sediments were deposited on the shore gravels. Conglomerate beds which are not basal also occur, and point to changes in the conditions of sedimentation even where unconformities were not developed.

The Proterozoic systems contain thick and extensive beds of quartzite, composed chiefly of grains of quartz, firmly cemented.



Fig. 346.—Section of the Proterozoic at a point in northern Michigan (*Ar*), Archean granite; *Ala* (Ajibik quartzite), *Als* (Siamo slate), and *Aln* (Negaunee [iron-bearing] formation) are Huronian formations. *Aui* (Ishpeming formation) and *Aum* (Michigamme formation) are Animikean formations. *Aed*, eruptive diabase or diorite. Length of section, 3 miles. (U. S. Geol. Surv.)

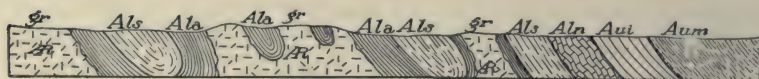


Fig. 347.—Section showing the relations of the Archean, Huronian, and Animikean at one point in the Marquette (N. Mich.) region. *Argr* Archean granite; *Ala* (Ajibik quartzite), *Als* (Siamo slate), and *Aln* (Negaunee [iron-bearing] formation) are Huronian formations. *Aui* (Ishpeming formation) and *Aum* (Michigamme slate) are Animikean formations. Length of section, 2 miles. (U. S. Geol. Surv.)

The quartz grains probably came from granitic rocks, and their separation from the other materials of the rock indicates the thorough decomposition of the rock, and ample opportunity for the rolling and rounding of the grains before they came to rest. As the quartzites of the Proterozoic are thousands of feet thick in some places, great bodies of rock must have been decomposed to furnish so much sand. There are also great beds of *shales*, or their metamorphic equivalents, which are interpreted as the clayey products of the decomposition which set the quartz free. *Limestone* also is present, from which it is inferred that the sea of the time had become calcareous by processes similar to those now in operation (p. 290), and that a portion of the calcareous content of

the waters was extracted and deposited. Figs. 346 and 347 show sections of the Proterozoic rocks in the Lake Superior region.

The inference that these ancient sediments were deposited in the same manner as the sediments of modern times is supported by the ripple- and other shallow-water marks on the sandstones and shales, and by their lamination and stratification, all of which are similar to those of sediments now being deposited.



Fig. 348.—Diagram showing a common surface relationship between Archean (*AR*), Proterozoic (*al*), and Cambrian (*C*). The Proterozoic (Algonkian) formations appear at the surface between younger and older formations.

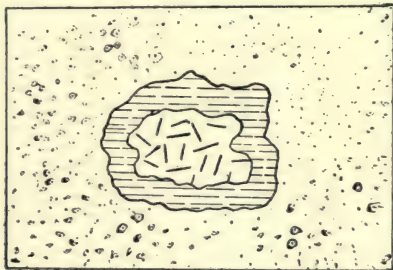


Fig. 349.—Diagrammatic map showing the formations shown in section in Fig. 348.

Geographic relations of the exposed Proterozoic to the Archean.

Proterozoic rocks appear at the surface in many parts of North America, but in few regions have they been clearly separated from the Archean, and in very few have their subdivisions been worked out. Fig. 341 shows the area where rocks of known Proterozoic age lie at the surface, together with areas where they have not been differentiated from the Archean. In many places, the Proterozoic rocks at the surface are near areas of exposed Archean.

That the Proterozoic formations should be exposed most commonly about the borders of the Archean is made clear by Fig. 348, which shows, in section, the general relations of the Proterozoic systems (*Al*) to the Archean (*R*) below, and to younger formations (*C*) above. The same relations are shown in ground-plan in Fig. 349. While the relations shown in these diagrams are common, there are areas of Archean not surrounded or bordered by exposed Proterozoic formations, and areas of the latter not associated with



Fig. 350.— Diagram showing how Proterozoic rock (*Al*) may fail to outcrop about Archean (*R*).

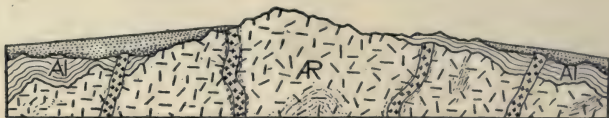


Fig. 351.— Diagram showing how Proterozoic rock (*Al*) may outcrop on one side of an area of Archean (*R*) and not on the other.

exposed Archean. Various relations of the two are illustrated by Figs. 350 and 351.

It is to be borne in mind that the map (Fig. 341) shows only the exposed areas (so far as known) of the Archean and Proterozoic. The Archean is presumably universal, beneath other formations. The Proterozoic system is not universal, but its real extent is much greater than the area where it appears at the surface. Thus the Proterozoic beds of Wisconsin are probably continuous beneath younger formations with the Proterozoic beds of southwestern Minnesota, and these in turn with those of Missouri and Texas on the south, and with those of the Black Hills and Rocky Mountains on the west.

THE PROTEROZOIC OF THE LAKE SUPERIOR REGION

The Proterozoic formations have been most carefully studied and their relations are best understood in the region about Lake

Superior, and the formations of this region have become, in some measure; the standard of comparison for the Proterozoic group as a whole. The Proterozoic formations of this region are of great thickness, and are divisible into four great unconformable systems, the relations of which to one another, to the Archean below and to the Cambrian above, are shown diagrammatically in Fig. 344. Not all of the four systems are present at all points in this region and Fig. 344 shows but three of them. They are now classified as follows:¹

Earliest Paleozoic	Cambrian
	<i>Unconformity</i>
	4. Keweenawan
	<i>Unconformity</i>
Proterozoic	3. Upper Huronian (or Animikean)
	<i>Unconformity</i>
	2. Middle Huronian
	<i>Unconformity</i>
	1. Lower Huronian
	<i>Unconformity</i>
Archeozoic	Archean

*The Huronian Systems*²

The first three systems of the Proterozoic group have much in common. All are dominantly sedimentary, and each includes formations of the common sorts of clastic rock or their metamorphosed equivalents, together with limestone and beds of iron ore, the last derived by alteration from beds of sediment which were ferruginous at the outset. Since none of the limestones are known to contain fossils, their organic origin cannot be affirmed. Each of the three periods of sedimentation represented by the Huronian systems was long, though their duration is unmeasured. Each system contains much igneous rock, some of which was extruded while sedimentation was in progress, and some intruded into the sediments after their deposition. Locally, igneous rock is more abundant than sedimentary.

The unconformable relations of the three Huronian systems, and the unconformity of the third below the Keweenawan, show that after the deposition of the first, second, and third systems

¹ Jour. Geol., XIII, p. 161.

² The name Huronian comes from the area north of Lake Huron, where these formations were first differentiated.

respectively, geographic changes occurred, resulting in erosion where sedimentation had been in progress.

The source of the material for the sedimentary part of the first of these systems was doubtless the exposed part of the Archean;



Fig. 352.— Map showing (in black) the position of the iron-producing areas in the Lake Superior region. 1, Michipicoten district; 2, Kamanistquia and Matawin district; 3, Steep Rock Lake and Attikokan district; 4, Vermilion district; 5, Mesabi district; 6, Penokee-Gogebic district; 7, 8, and 9, Marquette, Crystal Falls, and Menominee districts.

the source for the sedimentary part of the second system was the exposed part of the Archean and the Lower Huronian systems, and the source for the sedimentary part of the third system, the exposed parts of all older formations.

In places, the sedimentary rocks still remain in the condition of conglomerate, sandstone, and shale, though more commonly the sandstone has been changed to quartzite or quartz schist, and the shale to slate or schist. Some of the igneous rock remains massive, while some of it has been changed to schist. The rocks which are least altered are, as a rule, those which have been least deformed, and in places they are still nearly horizontal, as when first deposited. The movements which deformed and altered the second system

must have affected the first, while those which affected the third must have affected both the older systems. The oldest system is, on the average, most metamorphosed, and the youngest least.

Carbonaceous slates. One of the significant formations of this region is black shale or slate, the color of which is due to the presence of carbon, often in considerable quantity. The content of carbon is thought to imply the existence of life when the sediments were deposited. Where the rocks are highly metamorphic, the black shale has been changed to graphitic schist.

Iron ore. Another important formation is iron ore. Here belong the iron ores of the Mesabi (Minn.), Penokee-Gogebic (Wis. and Mich.), and Menominee (chiefly Mich.) regions (Fig. 352). The ore is in the form of ferric oxide (chiefly hematite, Fe_2O_3), but in this form it represents an alteration from iron-bearing cherty carbonates, and sediments containing ferrous silicate. The alteration was brought about by ground-water, circulating through the rocks.

The region about Lake Superior yields more iron ore than any other area of equal size in the world. In 1907, the aggregate production of this region was 41,526,579 long tons,¹ which was more than 78 per cent of all that was produced in the United States that year; of this, the Mesabi region produced nearly 27,245,441 tons.

The iron ores of this region are partly in the Archean (about Vermilion, Minn.), partly in the older divisions of the Huronian group (about Marquette, Mich.), but most largely in the Animikean (Menominee and Gogebic regions, Mich. and Wis., the Mesabi region of Minn., and some of the ores about Marquette). The following table gives the production in tons for these several regions for certain years preceding 1906:

(Long tons; maxima for each region in *Italics*.)

	1890	1895	1900	1905	1907
Marquette	2,863,848	1,982,080	3,945,068	3,772,645	4,167,810
Menominee	2,274,192	1,794,970	3,680,738	4,472,630	4,779,592
Gogebic	2,914,081	2,625,475	3,104,033	3,344,551	3,609,519
Vermilion	891,910	1,027,103	1,675,949	1,578,626	1,724,217
Mesabi		2,839,350	8,148,450	20,156,566	27,245,441
Total,	8,944,031	10,268,978	20,564,238	33,325,018	41,526,579

¹ Mineral Resources of the United States.

Thickness of rocks. The thickness of the Huronian systems is difficult of measurement, because of their wide-spread deformation, but if the maximum thickness of the individual formations of different localities is taken, the aggregate thickness is not less than three miles. Such thicknesses, however, are rarely attained in any one locality.

The following section from the Marquette region gives an idea of the sequence of formations in one place, and may be regarded as fairly typical for the region:

Upper Huronian	{	Michigamme slate and schist. Several thousand feet (maximum) in thickness.
		Ishpeming formation, largely quartzite. 1,500 feet (maximum) thick.
Middle Huronian	{	Negaunee formation or series (slate, schist, jaspilite, iron ore, etc.). 1,500 feet (maximum) thick.
		Siamo slate. 1,200 feet (maximum) thick.
		Ajibik quartzite, (sometimes schistose). Nearly 1,000 feet (maximum) thick.
Lower Huronian	{	Wewe slate (including some other sorts of rock). More than 1,000 feet (maximum) thick.
		Kona dolomite (some elastic beds). More than 1,300 feet (maximum) thick.
		Mesnard quartzite. Several hundred feet (maximum) thick.

The Keweenawan System

Constitution, thickness, and relations. In some parts of the Lake Superior region, a fourth system of pre-Cambrian rocks, the Keweenawan, overlies the Upper Huronian. This system is unlike the Huronian systems in being composed more largely of lava-flows than of sedimentary strata.

The lava beds of the Keweenawan constitute its lower and larger part. The earlier flows seem to have occurred on the land, and to have followed one another at short intervals, for the surface of one flow was not sensibly eroded before the next overspread it. Later in the period, the intervals between the flows of lava appear to have become longer, and thin beds of sediment were deposited between successive sheets of igneous rock. Still higher in the system, the sedimentary beds increase in importance until, in the upper part of the system, the lava beds fail altogether, and there follows a succession of sandstones and conglomerates of great thickness.

In the valley of the St. Croix River, in northwestern Wisconsin and the adjacent parts of Minnesota, there are said to be 65 lava-flows and 5 conglomerate beds in succession, with neither top nor bottom of the system exposed.¹ Some of the igneous rocks, such as the gabbros of the Vermilion² and Mesabi³ regions, are intrusive (laccolithic). The laccolithic intrusions of the Mesabi region have occasioned extensive metamorphism in the rocks into which they were intruded. The igneous rocks of the system consist principally of gabbros, diabases, and porphyries; but other varieties are also present.

The sedimentary rocks of the system were derived largely from the igneous rock, and their character is such as to indicate that they accumulated rapidly. The thickness of the sedimentary beds has been estimated at some 15,000 feet.

Estimated thicknesses. It is important to note the meaning of the great thicknesses sometimes assigned to sedimentary and igneous formations. In the case of the Keweenawan, for example, the thickness of igneous and sedimentary rocks has been placed as high as 50,000 feet, or nearly ten miles. When great thicknesses of sedimentary rock show signs of deposition in shallow water (or perhaps on land), as in this case, it is commonly inferred that the bottom of the basin of deposition sank during the deposition to an amount corresponding approximately to the thicknesses. In some cases, the amount of sinking assumed *exceeds the greatest depth of the oceans*. Moreover, if sedimentary rocks accumulated to the thickness assumed, their lower parts would be down where high temperatures prevail, and where the pressure would be such that all crevices and pores would be obliterated, and the rock highly metamorphosed. As a result of uplift and erosion the deeper parts of these thick systems are sometimes exposed, and in many cases do not show the effects of great heat and pressure. In view of these considerations, two positions have been taken by geologists. (1) The correctness of the estimated thicknesses has been questioned, or (2), accepting the estimates, far-reaching theories of

¹ Hall, Bull. Geol. Soc. Am., Vol. XII, pp. 313-340.

² Clements, Mono. XLV, U. S. Geol. Surv.

³ Leith, Mono. XLIII, U. S. Geol. Surv.

crustal deformations have been built upon the supposed subsidence of the surface. It is therefore important to inquire whether the thickness of a series of sedimentary beds is a measure of the depth of the basin in which they were deposited, or of its subsidence while they were being laid down.

When the sea covers the continental shelf, deposition takes place both on it and on the slope to the abysmal depths of the ocean,



Fig. 353.—Diagram of a series of beds formed on the abysmal slope of a continent, or in some similar situation, showing that the thickness, as usually measured, *ef*, is not dependent on the depth of the basin, *cd*, and that a thick series does not necessarily imply subsidence, even when the exposed portions of it show evidences of shallow-water deposition at various horizons.

and to a slight extent on the bottom of the deep sea. When the sea is withdrawn from the surface of the continental shelf, the shore stands near the upper edge of the abysmal slope, and the heaviest deposition is on this slope. The result may be seen from Fig. 353. Sediment from the land, *a*, is carried to the sea and deposited on the steep slope. The upper part of the deposits on the steep slope takes place normally in shallow water, and from its exposed position must be subject to the action of currents and waves which give it the characteristics of deposits made in agitated water. These characteristics are interpreted, commonly, as the marks of shallow water.

The abysmal slope is usually 2° to 5° , and these are about the angles of dip of the beds laid down on it. Now when these beds have become accessible by deformation and erosion, they are measured along the surface, which may be represented by the line *eo*, Fig. 353. There are two common modes of measurement: (1) The beds are measured individually, or by groups, at right angles to

the bedding-planes, and the sum of the whole ascertained; or (2) the average dip of the beds is taken, and the distance across the truncated edges, *eo*, is measured, and the thickness of the whole, *ef*, computed. By comparing the line *ef*, representing the thickness of the series, with the line *cd*, the depth of the basin when the beds were deposited, a marked difference is seen. Moreover, the difference may vary so much that there is no necessary relation between the two. If the line *ef* is short, as it would be if the series had not been built far out, the thickness would be less than the depth of the ocean, *cd*; but if the line *ef* is long, as it would be if deposition were continued sufficiently long, the thickness of the series, would be proportionately increased, while *cd* might remain constant. In other words, *the thickness of the series may vary from any fraction of the depth of the basin to a large multiple of it.*

Similar considerations reveal a discrepancy between the vertical measurement and the thickness of the beds deposited subaërially. For example, the thickness of the beds of a volcanic cone is *less than the height of the cone which they form*, as will be seen from Fig. 354. Lava-flows which congeal as they spread, may give rise to a

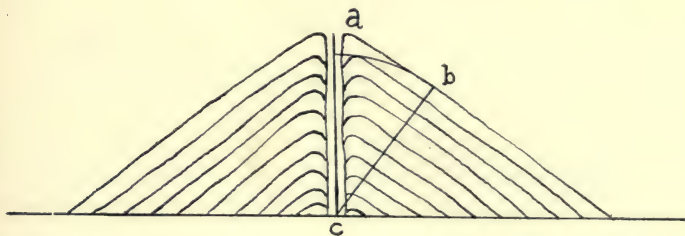


Fig. 354.—Diagrammatic illustration of relation of thickness of beds to height of accumulation in the case of volcanic cones. *ac*, height of cone; *bc*, aggregate thickness of layers, which is obviously less than *ac*.

series of great thickness, without implying contemporaneous sinking. Clastic beds formed by slope-wash may be laid down between the lava-flows without implying subsidence. In the case of the Keweenaw system, a congelation or deposition slope of 5° , extended horizontally a little more than one hundred miles (about half across the Keweenaw basin as it may have been) would

give the estimated thickness. To explain the present attitude of the beds, it is necessary to suppose that the basin was compressed laterally, so that the beds were upturned and somewhat sheared upon one another (Fig. 355).

It is not here affirmed that this is the whole of the explanation of the great apparent thickness of the Keweenaw system, though



Fig. 355.—Diagrammatic section illustrating the assigned change of attitude of a series of beds, like the Keweenaw, from an original depositional inclination, *A*, to a more highly inclined attitude, *B*, a comparatively simple change.

it seems to throw important light on it. The point here made is merely that great apparent thickness may and does arise in this way, and that inferences and doctrines that overlook this fact have an insecure basis.

Delta deposits furnish especially good illustrations of the point under discussion. If the Amazon were to build a delta out 200 miles, the ocean bottom remaining immovable at an average depth of four miles below the surface, and if the angle of deposition were 2° , the computed thickness of the series, according to current methods of measurement, would be about 7 miles. If the delta were built out 1,000 miles, the computed depth would be 35 miles. If a lake basin 100 miles wide and 1,000 feet deep were filled by sediment, the angle of deposition from either side being 3° , and the filling from each side out to the center, the thickness of the series *on each side*, measured by the above method, would be 13,800 feet. In this case 13,800 feet of sediment would accumulate in a basin 1,000 feet deep.

Dwelling on these aspects of the case, we almost reach the conclusion that the thickness of a series of beds, *as we usually measure thicknesses where they are great*, is independent of the depth of the basin. This, however, is pushing the case too far, for the considerations that have been urged apply only to deposition of the kinds specified, i. e., *deposition on appreciable slopes*. As originally laid down, the Keweenaw system probably fell far short of covering all of the Animikean.

Deformative movements. The sedimentary part of the Keweenaw series has usually been thought to imply marine submergence; but so far as now known the sediments may have been accumulated in an interior basin and may be more or less subaërial. It was probably during and at the close of this period that the Lake Superior



Fig. 356.—Diagram illustrating the development of the Lake Superior syncline. *A*, Archean; *H* and *A*, Huronian and Animikean; *K*, Keweenaw. (Irving, U. S. Geol. Surv.)

syncline (Fig. 356) was formed, in part at least, and the Keweenaw rocks tilted toward its axis, both from the north and south. It is not to be understood that this syncline has remained a surface depression ever since. On the contrary, it was subsequently filled with sedimentary beds, and the basin occupied by the present lake is the result of later and relatively recent excavation. The deep bowing of the series explains, in part, the distribution of the exposed portions of the Keweenaw system, which comes to the surface chiefly about the Lake Superior syncline.

The deformation of the Keweenaw strata of the region about Lake Superior was perhaps contemporaneous with deformation in other parts of the continent, and these changes are regarded as marking the beginning of the end of the Proterozoic era in this region.

As a result of the deformation at the close of the Keweenaw, some parts of the area where Keweenaw sediments had been

deposited were brought into such an attitude as to be subject to erosion, but the changes did not, as a rule, involve great folding of the strata. They are generally tilted, but only locally folded and faulted. In keeping with their structure, neither the sedimentary rocks nor the igneous rocks are greatly metamorphosed.

After the warping which followed the deposition of the Keweenawan system, the exposed surfaces of this and older systems suffered protracted erosion. Ultimately the land about Lake Superior sank again, and when the sea came back, a new series of sedimentary beds were deposited unconformably on the eroded surface of those which had preceded. The waters of the returning sea teemed with life, for the formation then deposited contains abundant fossils. This abundantly fossiliferous formation, resting unconformably on those which had preceded, is a part of the Cambrian system, the oldest system of the Paleozoic group.

Copper. The Keweenawan system contains the most extensive deposits of native copper known. The metal occurs in the pores and cracks of the igneous rock, and in the interstices between the pebbles and grains of some parts of the sedimentary beds. In the conglomerate at some of the richer mines, the copper is so abundant as to be an important cementing material of the rock. In its present form, it is believed to be a precipitate from aqueous solution, and to have been concentrated by ground-water. The original source of the metal was probably the igneous rock itself.¹

In 1875 the Keweenawan formation of northern Michigan yielded 16,089 tons of copper, or about 90 per cent of all that was produced in the United States. In 1905, the same area yielded 102,807 tons, but this was only about 26 per cent of the copper produced in the country that year.²

General Considerations Concerning the Lake Superior Proterozoic

Duration of time. It is difficult to conceive of the great lapse of time involved in the history of the Proterozoic era. The estimates give an aggregate thickness of more than 30,000 feet for the

¹ For discussions of the copper, see Irving and Van Hise, Mono. V, U. S. Geol. Surv., and Chamberlin, Vol. I, Geology of Wisconsin.

² Mineral Statistics for 1905, U. S. Geol. Surv.

sedimentary rocks of the Proterozoic systems. The accumulation of so much sediment would in itself mean a vast lapse of time, and when it is remembered that the four systems are separated from one another by unconformities, each of which may represent as much time as that involved in the accumulation of a system, it will be seen that the duration of the Proterozoic era was exceedingly long, possibly comparable to all succeeding time. The duration of the era cannot be stated in numerical terms, but it would appear that it should be spoken of in terms of tens of millions of years, rather than in terms of a lesser denomination.

Destruction of rock implied. Thick beds of sediment mean the destruction of a still larger volume of older rock, for much of the more soluble part of the rock destroyed does not appear in the sedimentary formations. It is important to note that a large part of the Proterozoic sediments were produced by the *mature decomposition* of older rocks. It is scarcely too much to infer that the materials of the larger part of the great formations of quartzite, slate, and shale first became soils on the surface of the parent areas, and that their removal was at a rate comparable to that of their renewal by rock decay. This point is of significance because it implies the existence of climatic conditions and geologic processes comparable to those of the present time.

If the Archean lands in the vicinity of Lake Superior were high enough at any time to furnish the thick sediments of the Proterozoic, their height would perhaps have surpassed any existing elevation, but it is not probable that such elevations existed at any time. It is more probable that as erosion proceeded, the land reacted by rising slowly, or that the sea bottom sank, drawing off the waters and leaving the land *relatively* higher. In this way, degradation and elevation may have been in progress at the same time, and the one process may never have got far ahead of the other. It is believed by some geologists that the removal of sediments in large quantities from the land would result in its rise, and that their deposition on the sea bottom would cause that to sink. The doctrine that the surface of the lithosphere sinks and rises under increase and decrease of load is one phase of the general theory of *isostasy*.

Succession of events. Reviewing the succession of events in the Lake Superior region, we find (1) that the land was high enough, after the Archean rocks came into existence and were deformed, for its surface to suffer prolonged erosion, but that the sites of the earliest sedimentation are unknown. (2) The Archean land then sank or was so eroded or deformed as to permit the deposition of the Lower Huronian sediments on portions of its eroded surface. (3) The area of the former Archean land, together with some part of the Lower Huronian system about it, was then brought into such an attitude, presumably by crustal warping, that it was subject to a long period of erosion, with contemporaneous sedimentation elsewhere. During the time of the deformation, the rocks involved were somewhat metamorphosed. (4) Again the land seems to have sunk, allowing the sea (or at any rate, conditions for deposition) to cover a large part of the territory which had been subject to erosion, and to deposit upon its eroded surface the sediments of the Middle Huronian system. (5) After this long period of sedimentation, certain tracts seem to have emerged, exposing the landward border of the Middle Huronian system, and all the older rocks not covered by it, to erosion. The emergence of areas of Middle Huronian sedimentary formations was accompanied by some deformation and metamorphism. (6) This period of erosion was followed in turn by another period of submergence, when sediments (the Animikean) were laid down again in the Lake Superior region, this time on the eroded surface of the Middle Huronian or some older system. (7) Deformation, accompanied by emergence and followed by erosion, succeeded this third period of Proterozoic sedimentation. (8) Flows of lava of great magnitude were then poured out upon the surface of the land over considerable areas, and intruded into existing terranes. Before the outflows ceased, sedimentation began again in the region, and soon predominated, the lavas and sediments making the Keweenawan system. (9) After the deposition of this system, much of it was exposed to erosion.

This succession of events implies repeated changes of relative level of land and sea in the Lake Superior region during the Proterozoic era. We shall see that such changes are confined neither

to this time nor to this region. Geological history makes it clear that changes in the relations of sea and land are among the notable events of the earth's history, even to the present time. Since many other changes are dependent on them, they are believed to furnish the best basis for the subdivision of geological history.

It is not now possible to determine the extent of the crustal oscillations which took place during the Proterozoic era; but enough is known of the extent of the area in North America at the close of the Proterozoic to make its cartographic representation instructive. The area not covered by the early Cambrian beds (Fig. 357) was land at this time, and the continent was probably much more extensive than this statement implies.

Metamorphism. The Lower Huronian rocks are, on the whole, more highly metamorphosed than the Middle Huronian, and these are more generally altered than the Animikean, while the Keweenawan formations are metamorphosed scarcely at all. On the other hand, the Animikean beds are locally as highly metamorphic as the Lower Huronian, indicating intense dynamic action, at least locally, after the deposition of the third great system. Since different sorts of rock behave differently under dynamic action, it follows that some beds are much more highly metamorphic than others associated with them, even though subjected to the same forces.

There is scarcely a phase of metamorphism which the Proterozoic rocks do not show. The schists, slates, and gneisses are especially the product of dynamic metamorphism; the quartzites are the products of extreme consolidation by cementation; the iron ore is the product of metasomatism, effected by ground-waters, while other phases of metamorphism are due to the heat of intruded rock. It is not to be understood that the metamorphism of any considerable body of rock is effected by any one process alone. Dynamic action, which seems on the whole the most important factor in metamorphism, always generates heat, and high temperature, especially in the presence of water, facilitates chemical and mineralogical change. So, too, in the case of igneous intrusions, there is often great dynamic action as well as great heat, and water, an agent of chemical change, is always present.

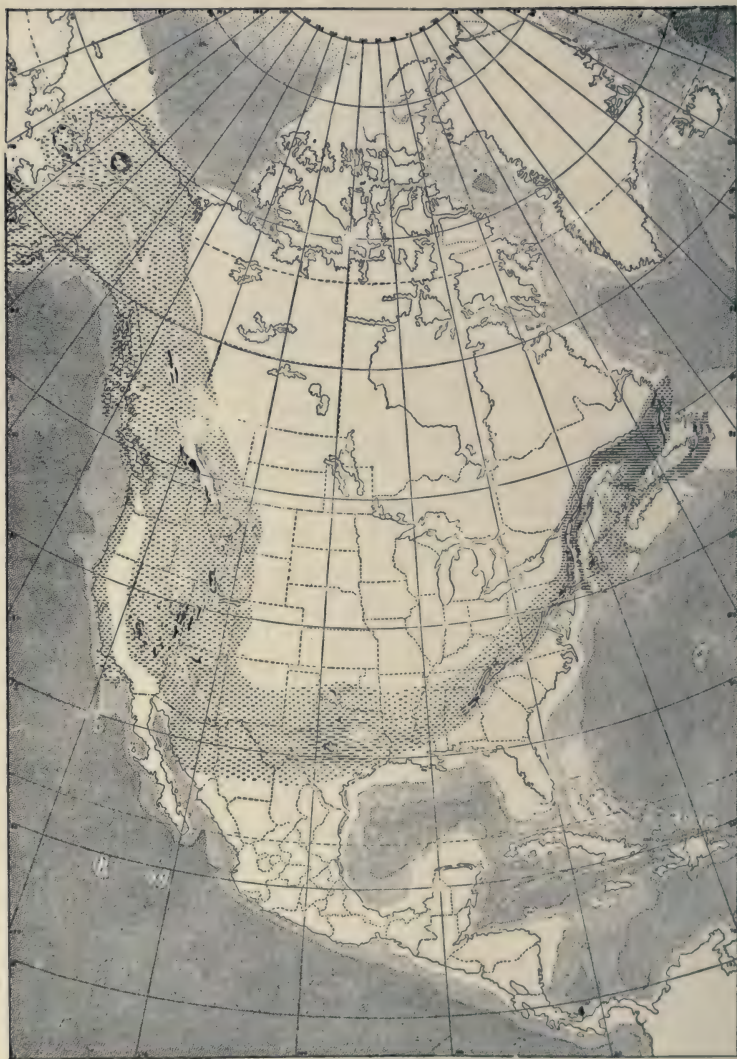


Fig. 357.— Map showing the outcrops (in black) of Lower and Middle Cambrian formations. The areas shaded by lines represent regions where the formations are believed to exist, though not exposed. The longer the lines, the better the basis for belief in the existence of the beds.
(Continued at bottom of page 471.)

Sequence of events elsewhere. A series of events consonant but not necessarily identical with those of the Lake Superior region was probably in progress about every other area of Archean rock, during the Proterozoic era; but it does not follow that about every other Archean land area four great systems of rocks were laid down during this long era. About some such areas there may well have been three, or two, systems of Proterozoic rocks instead of four, while about others, continuous sedimentation may have been in progress from the beginning of the Huronian period to the end of the Keweenawan.

Proterozoic Rocks in Other Regions

Pre-Cambrian sedimentary formations occur in many other parts of North America, in relations to the Archean similar to those already described. On the whole, it may be said that they resemble the rocks of the Proterozoic systems about Lake Superior as closely as could be expected under the general principles already set forth.

Some of the more important occurrences of Proterozoic rocks outside the Lake Superior region are the following: (1) In an extensive area north of the Great Lakes; (2) in the eastern provinces of Canada; (3) in the Adirondacks; (4) in isolated patches in the Mississippi basin, in Wisconsin, northwestern Iowa and adjacent parts of Minnesota and South Dakota, in the Black Hills of South Dakota, in southeastern Missouri, and in Oklahoma; (5) in Texas; (6) in the Piedmont belt of the eastern part of the United States; and (7) at various points in the Cordilleras.

In some of these localities, the rocks are chiefly sedimentary or meta-sedimentary, while in others they are partly or even largely igneous. Thus in the Black Hills, the Proterozoic rocks consist of closely folded meta-sedimentary rocks, such as mica slates, quartzites, schists, etc., and intrusive igneous rocks. From the granite intrusions, the largest of which is eight or ten miles

The unshaded areas north of Mexico are believed to have been land during the early portion of the Cambrian period. The unshaded area south of the United States represents lack of knowledge. The shading within the area of the ocean is the same as in Fig. 341. The Middle Cambrian may be somewhat more extensive than the map shows. The area not covered by the early Cambrian formations, and probably a still larger area, was land at the end of the Proterozoic.

long and nearly as broad, numerous dikes penetrate the clastic beds; and furnish good illustrations of the metamorphosing effects of igneous intrusions.

In the *Adirondack region*, Pre-Cambrian rocks make up a large part of the Adirondack Mountain mass. They belong to two groups: (1) The central mass of the mountains, consisting of igneous rocks which were intruded into (2) a series of pre-Cambrian sedimentary rocks which surround and cover the base of the igneous mass.

The Cordilleran region. The axial cores of many of the older mountain ranges of the West are believed to be of Archean rock. In many of them there are thick series of sedimentary or meta-sedimentary rocks overlying the Archean and surrounding its outcrops, overlain in turn by Cambrian or younger strata. Rocks referred to the Proterozoic are found in the Medicine Bow and some other mountains of Wyoming; in the Bridger, Little Belt, Lewiston, and Livingston ranges of Montana, where some of them are fossiliferous; in British Columbia; in the Wasatch and certain lesser ranges of Utah; in several of the ranges of Nevada and Colorado, and in the Grand Canyon of the Colorado in Arizona. In most if not all of these localities, sedimentary beds predominate, but are accompanied by igneous rocks which are in part contemporaneous. The thickness of the Proterozoic rocks in these various localities is often great, and in most places they are unconformable on their base, and beneath overlying formations. In much of the northwest, however, there is conformity between the Proterozoic and the Lower Cambrian, according to present interpretations.

In the Canyon of the Colorado (Arizona) the pre-Cambrian formations are well exposed. The Proterozoic (Grand Canyon) group, more than 10,000 feet in thickness, here rests unconformably on the Archean, and is in turn covered unconformably by the Cambrian. The group is itself divisible into two systems by a slight unconformity. Here, as in Montana, a few fossils have been found.

In the eastern part of the United States.¹ There are large areas of metamorphic rock in the eastern part of the United States,

¹ See Bull. 86, U. S. Geol. Surv., and folios, U. S. Geol. Surv.

which were formerly classed as Archean. Their position is shown in Fig. 341. This belt of metamorphic rocks contains formations that were sedimentary, and those that were igneous. Some of them are probably Proterozoic, but the Proterozoic rocks here have not been generally differentiated from the Archean on the one hand, and from metamorphic Paleozoic rocks on the other.

Summary. While the correspondence of the Proterozoic rocks in these various regions with those of the Lake Superior region is not generally very close, it may be pointed out again that close correspondence is not to be expected, even if the rocks of different localities were contemporaneous in origin. The phases of sedimentation taking place about any land mass at any time are largely dependent upon the height of the land, the freeness of the exposure of its coasts, the climate, and the character of the formation suffering erosion. These various factors were as likely to be dissimilar as similar about the various centers of sedimentation. Igneous rocks form a not inconsiderable part of the Proterozoic systems, and there is no apparent reason why igneous activities in different regions should correspond either in time or in the nature of their products. Even deformations of the crust, which are the basis for the separation of the group into systems, need not have corresponded in different regions. It follows (1) that the number of systems bounded by unconformities within the Proterozoic, may not be the same in all regions; (2) that the thicknesses of the various systems may vary within wide limits; (3) that there need have been no close correspondence in the sorts of rock in different regions at the outset; and (4) that they may have been metamorphosed unequally since their deposition. The dissimilarity of the Proterozoic in different regions, as suggested by the preceding sketch, was, therefore, to have been anticipated.

Proterozoic Formations in Other Continents

Proterozoic formations are believed to exist in all continents. In more than one country where they have been studied, the pre-Cambrian sedimentary rocks are thought to belong to at least two systems, separated by unconformities. It is worthy of note that in Sweden, as about Lake Superior, iron ore occurs in these formations.

LIFE DURING THE PROTEROZOIC ERA

While the Proterozoic rocks do not generally contain fossils, there can be no doubt that life existed during the era. The lines of evidence are as follows: (1) The carboniferous shales, slates, and schists indicate the existence of life; (2) the occasional fossils¹ (especially in Montana and in the Grand Canyon of the Colorado) demonstrate the existence of life at that time; (3) the iron ore of these systems, although not originally deposited in its present form, has been thought to imply the existence of life; and (4) the limestone. It should be noted that limestone occurs near the base of the Lower Huronian. This rock was formerly regarded as demonstrative of the existence of life, but in recent years the belief has gained ground that considerable formations of limestone may have originated by precipitation from sea-water. This origin is suspected for many limestone formations which are free from fossils, and if the hypothesis is applicable to any extensive formation of limestone, it may be applicable to that of the Proterozoic. But even without reliance on this sort of rock, the occasional fossils leave no doubt of the existence of life in this era. The best-preserved fossils are those of Eurypterus-like crustaceans. There are also tracks of two genera of worms, and other undetermined forms. Besides these certain fossils, there are obscure forms which appear to be referable to brachiopods and pteropods. It is significant that the oldest definite fossils yet found are forms well up in the animal kingdom and that they occur (in Montana) 9,000 feet below the unconformity between the Proterozoic and the Cambrian.

CLIMATE

Since inferences concerning the climate of any period are drawn chiefly from fossils, and since fossils are exceedingly rare in the Proterozoic strata, they afford little warrant for any conclusion concerning the climate of the era. It may be noted, however, that conglomerate beds which have been interpreted as glacial are

¹ For summary of knowledge concerning pre-Cambrian fossils, see Walcott, *Bull. Geol. Soc. Am.*, Vol. 10, pp. 199-244.

² Coleman, *Jour. Geol.*, Vol. XVI, p. 149. The evidence of the glacial character of these beds is open to question.

found in the Proterozoic of Canada,² that glacial beds of somewhat uncertain age — late Proterozoic or early Cambrian — are also reported from Norway,¹ and that glacial formations of early Cambrian (or late Proterozoic) age exist in China.² Glacial formations are singularly out of harmony with the conceptions of the climate of early geologic time which have prevailed until recent times.

Map studies. Map studies should be carried on in connection with the chapters on the Archeozoic and Proterozoic. For this purpose, numerous folios of the U. S. Geological Survey are especially serviceable; so also are some of the maps and sections in various Reports of the same Survey, and of certain State Geological Surveys.

Some of the folios which are especially valuable for this purpose are the following; *Arizona*, Bradshaw Mountain, Clifton; *Colorado*, Needle Mountains, Ouray, Rico; *District of Columbia*, Washington; *Maryland*, Patuxent; *Michigan*, Menominee; *North Carolina*, Asheville, Cranberry, Mount Mitchell, Nantahala, Pisgah; *Virginia*, Harpers Ferry; *Wyoming*, Absaroka, Bald Mountain-Dayton, Cloud Peak-Fort McKinney, Hartville, Sundance. These folios show the structure and the relations of the Archean to the Proterozoic (Algonkian) at divers points, and the relations of both to younger rocks. These relations should be noted. The Structure Section Sheets of the folios afford the means for determining, more or less closely, the sequence of geologic events in the region concerned, such as the dates of deformations, the dates of igneous intrusions or extrusions, the dates of faulting, etc. The texts of the folios give brief descriptions of the formations, and concise statements concerning the sequence of geologic events in the regions concerned.

¹ Reusch, Norges geologiske Undersøegelse: Det nordlige Norges Geologi, 1891. Also Strahan, Quar. Jour. Geol. Soc., Vol. 53, 1897, pp. 137-146.

² Willis, Year-Book No. 3, Carnegie Inst., p. 382.

THE PALEOZOIC ERA

CHAPTER XVI

THE CAMBRIAN PERIOD

FORMATIONS AND PHYSICAL HISTORY

The great crustal movements which brought the Proterozoic era to a close converted a large area within the limits of the North American continent into land. This is shown by the geographic distribution of the basal strata of the Cambrian,¹ the oldest system of the Paleozoic era. Where accessible, the base of the system is, in most places, unconformable on underlying formations. The distribution of the successive parts of the system gives some idea of the relations of sea and land throughout the period, for most of the strata are of marine origin, as their fossils show.

The Subdivisions of the Cambrian and their Distribution

The Cambrian system has been divided into three series, known as the Lower, Middle, and Upper Cambrian, respectively. Other names are sometimes assigned to these divisions. Thus Georgian (Vt.), Acadian, and Potsdam (Saratogan) (N.Y.), names of localities where the corresponding divisions of Cambrian were first differentiated in North America, are synonyms (in America) for Lower, Middle, and Upper Cambrian respectively.

The Lower Cambrian. The Lower Cambrian formations are known in North America only near the eastern and western borders of the continent (Fig. 357). In the east, they are found in the Appalachian belt and at some points farther east; in the west, they are found in various states between the 110th and the 120th meridians. In both the east and the west, the strata contain marine fossils. The strata of the east were accumulated in straits, sounds, etc., rather than on the shores of the open sea.

¹ A summary of the literature on the North American Cambrian prior to 1892 is given by Walcott in Bull. 81, U. S. Geol. Surv.

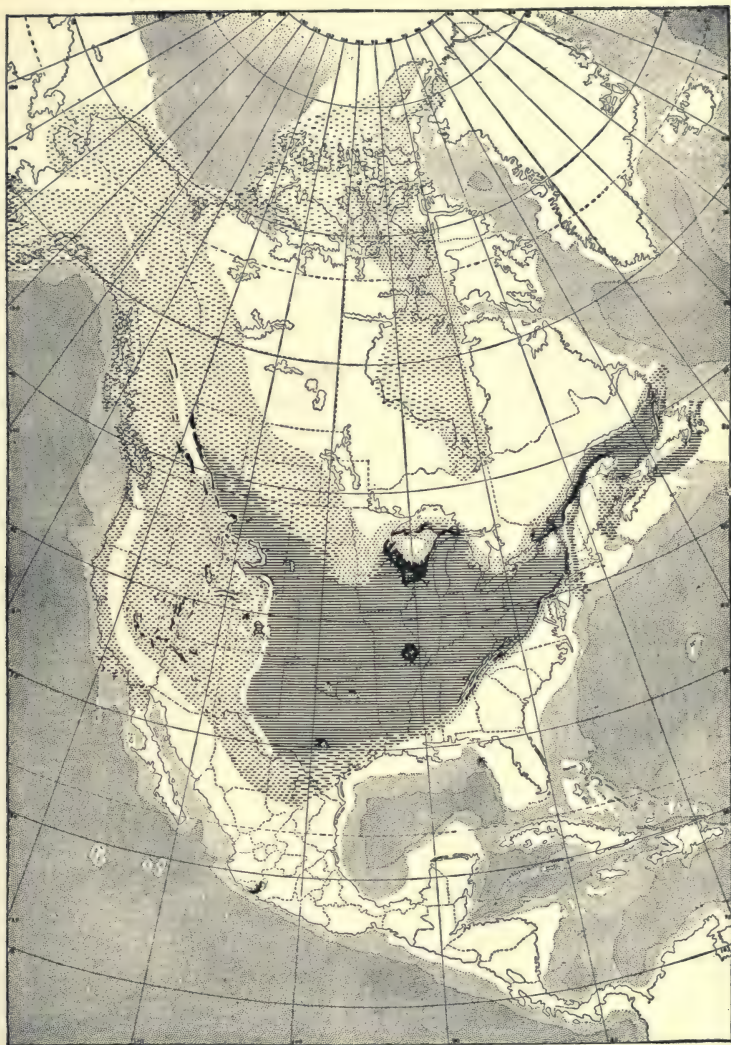


Fig. 358.— Map showing the Upper Cambrian formations. The outcrops are shown in black. The continuous lines represent areas where the Upper Cambrian formations are confidently believed to exist, though concealed. The dashes represent areas where there is some reason for believing them to exist. The dotted areas represent areas from which the Upper Cambrian is believed to have been removed by erosion. The unshaded areas have the same meaning as in Fig. 357.

The great tract between the Appalachian Mountains on the one hand, and western Montana and Utah on the other is believed to have been land during the early part of the period. From this land, sediments were probably being carried to the sea on either hand. These sediments, subsequently cemented into rocks, made some of the shales and sandstones of the Lower Cambrian.

The unconformity between the Lower Cambrian and its base represents what is sometimes called a "lost" interval. This designation for such an interval is not altogether appropriate, for the unconformity records a time of exposure and erosion, followed by submergence and deposition.

The Middle Cambrian. The strata of the Middle (Acadian) series of the Cambrian system are found with those of the Lower Cambrian, and in addition they are known in Texas, Oklahoma, Arizona, some parts of Montana, and perhaps elsewhere. Since the Middle Cambrian beds contain marine fossils, their distribution indicates that the continent was being invaded by the sea from the south before the close of the Middle Cambrian epoch. Like the preceding series, the Middle Cambrian beds are absent from much of the interior, if present identifications are correct. Where the Middle Cambrian rests on the Lower, the two are generally conformable.¹ Where the Middle overlaps the Lower, it is unconformable on older formations.

The Upper Cambrian. In the Later Cambrian (Potsdam or Saratogan) epoch, the sea covered much more of the continent, for the Potsdam series covers not only the eastern and western borders of the continent, but much of the interior as well. The Upper Cambrian is conformable on the Middle Cambrian in the east and west, but in the interior it rests unconformably on pre-Cambrian formations. Fig. 358 shows something of the distribution of the Cambrian system as a whole (see explanation beneath the Fig.)

Great submergence during the Cambrian. The distribution of the several series of the system shows that *the great physical event of*

¹ Ulrich and Schuchert think that the Appalachian synclinalorium of Early Cambrian times was largely drained at the close of that epoch. Bull. 52 (Paleontology 6) N. Y. Mus. Rept. of the State Paleontologist, 1901, p. 636.

the Cambrian period in North America was the progressive submergence of the continent. Theoretically, this submergence may have been brought about by a rise of the sea or by a lowering of the land, or by both together. Both the lowering of the land and the rise of the sea may be due to gradation, to diastrophism, or to the two combined.

Gradation a possible cause of submergence. Gradation is perpetual and inevitable where land and sea exist. The waves attack the land along its borders, and the agents of land degradation lower its surface. The former is a direct cause of encroachment of sea upon land, and the latter is an indirect cause, since all sediments transported from land to sea displace an equal volume of water, and raise the surface of the sea correspondingly. Small as this rise is for any brief period, its effect is to cause the sea to advance on the land; and the lowering of the land by degradation at the same time, increases the area of the advance. *If continued long enough*, shore-cutting about the borders of the lands, down-cutting over the whole surface, and the accompanying rise of the sea-level, must inevitably cause the water to cover the continents, and to spread deposits over all but the last remnants of them, *provided there is no deformation of the body of the earth in the meantime.*

It has been computed that if the earth, in its present condition, were to remain without deformation long enough for the continents to be base-leveled, the deposition of the sediments thus derived in the sea would raise the sea-level about 650 feet. This would submerge a large part of the base-leveled land. The evidence of gradation in the Cambrian period is clear and firm. Most of the sediments which make up the Cambrian system of rocks were eroded from the land and deposited in the sea. This lowered the land and raised the sea. Gradation was, therefore, a factor in the submergence of the continent, and there is evidence that great progress was made toward the base-leveling of America and other continents, before the close of the Cambrian period. Base-leveling *implies a nearly undisturbed attitude of the land and sea*, and hence in itself favors the view that no great deformation affected the continent while it was going on. In harmony with this view, there is an absence of direct evidence of profound deformation during the

Cambrian period. There is therefore a presumption against much diastrophism during the period.

If gradation were the *sole* agency involved in the submergence of the lands, the advance of the sea should have been steady, though not necessarily equal in rate at all times and places. Without going into details, it seems certain that there were changes in the areas of deposition other than those which can be accounted for by gradation, but none of these changes imply warpings of pronounced type like those recorded in the rocks of the Proterozoic and Archeozoic eras.

Deformation as a cause of submergence. The deformations which cause submergence of land (and emergence of sea-bottom) may be either *superficial*, involving the rocks down to depths of a few miles at most, or *deep-seated*, involving the rock to much greater depths. One or two phases of deformation may be mentioned.

1. **Lateral spread or continental creep.** The continents stand about 15,000 feet above the ocean bottom. Their weight causes a pressure of 15,000 to 20,000 pounds to the square inch on their bases. This pressure *tends to cause the continents to spread by creep into the ocean basins*, on the same principle that a great body of ice, such as an ice-sheet, spreads. Spreading is opposed by the hydrostatic pressure of the oceans against the sides of the continental platforms. This is some 5,000 pounds per square inch at the bottom, so that there remains an unbalanced pressure of 10,000 to 15,000 pounds per square inch, tending to cause creep. Is this enough to overcome the strength of the rock, which opposes creep? Even the lesser of these figures is equal to the crushing strength of some of the weaker rocks, and is a notable percentage of the crushing strength of even the strongest. Under less pressure than this, the rock in mines is often observed to creep. It is not improbable, therefore, that such a pressure, constantly exerted for a prolonged period, might cause some spreading of the great continental platforms, and hence (1) some lowering of their surfaces, (2) some submergence about their borders, and (3) at the same time some rise of the sea-level. Many phenomena which cannot be cited here seem to lend support to this hypothesis of lateral creep,¹ but its efficiency is not determined.

¹ Chamberlin and Salisbury, *Earth History*, Vol. II.

2. **Adjustments between continental and oceanic segments, a possible cause of submergence.** It has been shown¹ recently that there is a plane about 100 miles below the surface of the earth where the pressure downward beneath the overlying continental areas, is equal to the downward pressure beneath the overlying oceanic areas, in spite of the fact that the surfaces of the continents are, on the average, three miles above the ocean bottoms. The reason is that the rock beneath the oceans is denser than that beneath the continents. At all horizons above this *isostatic* plane at the depth of about 100 miles, a column of average continental rocks measured downward from the surface of the land, weighs more than a similar column of sub-oceanic rocks. This tends to aid the spreading movement noted above, and so tends to bring about submergence of the land. A similar state of things probably prevailed in Cambrian times. It appears however that notably elevated regions, like the Cordilleran tract, stand higher than they would if they were in isostatic balance.² This lack of balance may give rise to special movements to secure a more perfect equilibrium, and hence to regional or local deformations. During any great period of deformation, like that at the close of the Proterozoic, it is probable that some portions of the crust were pushed up above a position of equilibrium, and later tended to settle back. Other portions may have been depressed below the position of equilibrium, and later tended to rise. Such movements would be unsymmetrically distributed, and might result in slow and quiet, but unequal warping.

3. **Other adjustments, as possible causes of submergence.** Various other changes and adjustments of the surface of the different parts of the lithosphere, such as the unloading of the continents by erosion and the loading of the ocean basins by deposition, the outpourings of lava, and unequal additions or losses of heat in different places, may also have helped to cause submergence or emergence of the lands.

Basis for the Subdivision of the Cambrian

We have now to inquire the means by which the Cambrian

¹ Hayford, Washington Acad. of Sci., Vol. VIII, 1906, pp. 25-40.

² Putnam and Gilbert, Bull. Phil. Soc. Washington, Vol. XII, pp. 31-75, and Gilbert, Jour. Geol., Vol. III, p. 351.

strata may be recognized, and further the means by which the Lower Cambrian may be distinguished from the Middle, and the Middle from the Upper.

Superposition. Where a formation is conformable on another of known age, as the Middle Cambrian on the Lower, the presumption is strong that the upper was formed after the lower, without interruption. In this case, the approximate age of the upper is known. But where one formation is unconformable on another of known age, the stratigraphic relations between them do not determine the age of the upper, beyond the general fact that it is younger than the lower.

Fossils. The Cambrian is the oldest system of rocks known to contain abundant fossils. Most of them represent the shells or other hard parts of marine animals buried in the sands and muds at the time they were deposited. The fossils in the strata of any division of the Cambrian constitute the known *fauna* of that stage, though it is not to be supposed that fossils of all the species that lived have been preserved.

The Lower Cambrian series contains certain fossils which are

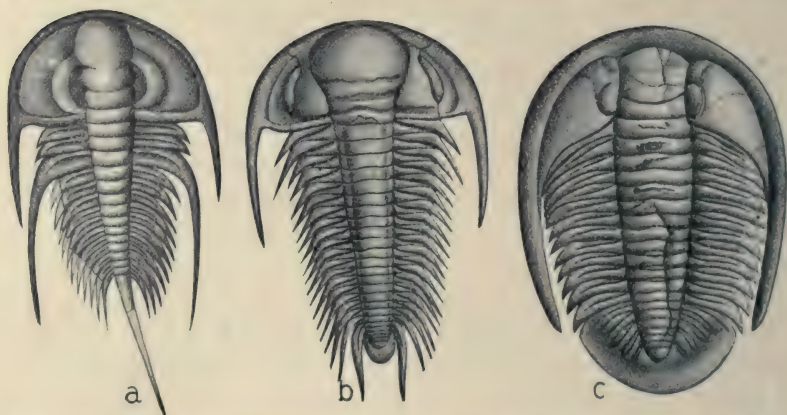


Fig. 359.—Three characteristic Cambrian trilobites: *a*, *Olenellus gilberti* Meek; *b*, *Paradoxides bohemicus* Boeck; *c*, *Dikellocephalus pepinensis* Owen.

distinctive. Among them are species of a genus of trilobites known as *Olenellus* (Fig. 359, *a*). Along with the representatives of this

genus, many other species of various types of life are found. To the aggregate, the name *Olenellus fauna* has been given, and *Olenellus Cambrian* is synonymous with Lower Cambrian and with Georgian. It is not to be understood that representatives of the genus *Olenellus* are found in the Lower Cambrian everywhere,¹ or that other genera of trilobites are absent.

Where formations representing the whole of the period are present, the fossils in the higher beds are not the same as those below. At no single plane is there, as a rule, a very striking change in species, but in successively higher beds some of the species found below disappear, and new species come in, as if to take their places. These variations show that the inhabitants of the sea changed as time went on. At about that stage in the Cambrian system where the genus *Olenellus* drops out, the genus *Paradoxides* (Fig. 359, *b*) appears on both sides of the North Atlantic basin. The other species associated with *Paradoxides* are somewhat different from those associated with the genus *Olenellus*. The *Paradoxides* and their associates constitute the *Paradoxides fauna*, a fauna which includes also many species of other genera of trilobites, and many species of other classes of animals not related to trilobites. By general agreement, the Middle Cambrian, on both sides of the North Atlantic, is defined by the *Paradoxides fauna*, so that *Paradoxides Cambrian* is synonymous with Middle Cambrian and with Acadian (p. 476). In the western part of North America, and on the opposite side of the North Pacific as well, the Middle Cambrian does not contain *Paradoxides*, but *Olenoides*, and its fauna is known as the *Olenoides fauna*, but it is none the less distinct from fauna of the Lower Cambrian.

In like manner the *Paradoxides* and *Olenoides* faunas are succeeded by another, known as the *Dikellocephalus fauna* (359, *c*), and this fauna characterizes the Cambrian strata above the Middle Cambrian. Geologists have agreed to define the Upper Cambrian as the series of strata carrying the *Dikellocephalus fauna*.

It is not to be understood that every species of the *Paradoxides fauna* is unlike every species of the *Olenellus fauna* below and the *Dikellocephalus fauna* above. This is not the case; but so many

¹ Walcott, Jour. of Geol., Vol. XVII, 1909.

of the species of the three faunas are different, that with a considerable number of species to judge from, their separation is possible by those familiar with Cambrian fossils.

In the discrimination of any of these faunas, an analogy with living animals is suggested. The present faunas of North and South America are reasonably distinct; but it does not follow that there are no species in common. Given a single animal, even an expert might not be able to say that it was from the one continent or the other, though with certain species even this might be done; but if a large number of animals from either continent are available, it is possible to determine to which continent, that is to which *geographic fauna*, they belonged. So with the several Cambrian faunas. They have some species in common, and such species do not distinguish the groups of strata which contain them from one another. But certain species are found only in the Lower, certain other species only in the Middle, and still others only in the Upper part of the system, and these species serve to distinguish the principal divisions.

Sequence of faunas based on stratigraphy. It is not to be understood that rocks which contain such faunas are classed together simply because they contain certain fossils. This is not the reason, or at least not the principal reason for grouping them together. The order of sequence of faunas is first determined *by the superposition of the strata*. The Lower Cambrian fauna could not be known to be older than the Middle Cambrian fauna, if the beds containing the former did not underlie beds containing the latter. In other words, *the primary basis for correlation by means of fossils is stratigraphy*.

Sedimentation in the Cambrian Period

Sedimentation in the Cambrian period appears to have followed the general laws that govern deposition in periods of comparative freedom from great deforming movements, and hence of progressive base-leveling. Most of the known Cambrian sediments were deposited in the sea, and their area may be regarded as a rough measure of the area of the sea at that time. Sedimentation was probably faster in the early stages of the period when the land-

area was largest and highest, and slower in the later stages after the land surface had been worn down by erosion and narrowed by the encroachment of the sea. Sedimentation was probably greater near the land, and less far from the shores in deep water.

Sources and kinds of sediments. As in other geologic periods, the land-derived sediments came from all formations then exposed to erosion. The sediments along the immediate borders of the land were doubtless different from those deposited farther from it. Even along shore there were considerable variations, both because of variations in the sources of the sediments, and because of differences in wave, river, and current action.

The Cambrian formations include all common phases of sedimentary rocks. There are conglomerates, presumably accumulated near the shores of the time; there are sandstones, the sand of which was deposited in shallow water where the waves were sufficiently vigorous to keep the mud from settling; shales representing the deposits made in stiller or deeper water; and beds of limestone representing, for the most part, the accumulations of shells, etc., where terrigenous sediments were not carried in quantity.

Geographic variations in the sediments. The distribution of these various sorts of sedimentary rocks shows that various kinds of detrital beds were accumulating in different places at the same time, and at the same place at different times. Not only this, but they were accumulated at very different rates. Thus the full section of the Middle Cambrian (all that was deposited during the whole of the Middle Cambrian epoch) seems to be present at many points, yet the thickness of the Middle Cambrian strata is far from uniform. Equal thicknesses of rock do not necessarily accumulate in equal periods of time.

The fact that in the northern interior of the United States the Upper Cambrian formation is generally of sandstone, and that this sandstone is wide-spread, indicates that the water was so shallow during its deposition that the waves were competent to roll sand long distances. Furthermore, the structure of the strata, with their cross-bedding (Fig. 266), ripple-marks, etc., shows that the whole of the thick series from bottom to top was deposited in shallow

water, and therefore on a surface which was gradually depressed, relative to sea-level, as the sediments were accumulated. The greater proportion of limestone (chiefly dolomite) in the Upper Cambrian of the southern and southeastern interior, points to clearer seas, but perhaps not to deep ones. The adjacent lands were perhaps too low to yield abundant sediment. Limestone is also an important part of the Upper Cambrian of the Rocky Mountains,¹ though clastic rocks predominate farther west. Where the Upper Cambrian is limestone, it is not usually sharply differentiated from the overlying Ordovician.

Distribution and Outcrops of the Cambrian System

The Cambrian formations were once as wide-spread as the Cambrian seas themselves, but they are not now present over all the area they once covered. The exposed edges of the strata have suffered erosion, so that the border of the system as it now appears about the areas of pre-Cambrian rock, is not its original

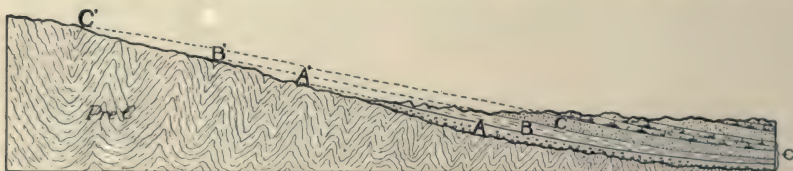


Fig. 360.—Diagram illustrating the relation of Cambrian formations, A, B, and C, to older rocks. The diagram suggests that the Cambrian formations have been eroded back from their original margins, A', B' and C'.



Fig. 361.—Diagram illustrating the general relations of Cambrian beds in the interior. The Cambrian, C, is represented as appearing at the extremes of the diagram, and as dipping below younger beds between.

border, and does not represent the shore-line of the Cambrian sea when its waters were most wide-spread. Fig. 360 represents the conditions which often exist. Each of the Cambrian formations, represented by A, B, and C, formerly extended farther to the left.

¹ Dawson, Bull. Geol. Soc. Am., Vol. XII, pp. 64-68.

The areas where the Cambrian formations are exposed are not to be confounded with the areas where they actually exist. The Cambrian formations are exposed, for example, in Wisconsin, in Missouri, and in Texas; but the strata of Texas are doubtless continuous, beneath younger formations, with those exposed in Missouri, and those of Missouri with those of Wisconsin, and these in turn with those of the Black Hills on the west, and with those of New York on the east (Fig. 361).

Position of outcrops. The map (Fig. 358) showing the areas where the Cambrian system is now exposed, reveals several points of significance. (1). Many of the outcrops occur in association with outcrops of the Archean and Proterozoic systems (Fig. 341). In some places, the exposed Cambrian lies along the border of the exposed parts of these older systems on one side only, while in others

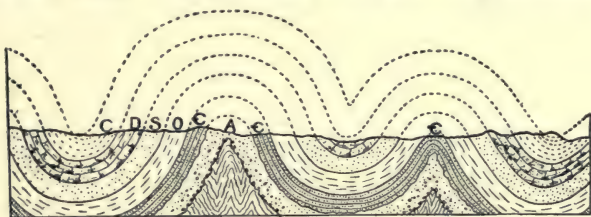


Fig. 362.—Diagram showing the positions of outcrops as determined by folds. The anticline at the right is represented as having been truncated in such a way as to expose the Cambrian, *C*, in a single belt; that at the left has been cut so as to expose pre-Cambrian formations, *A*, and the Cambrian, *C*, outcrops in two belts, one on either side of the older formation.

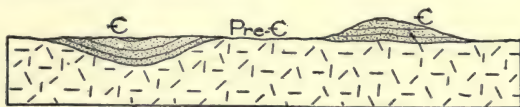


Fig. 363.—Figure to illustrate two sorts of isolated occurrences of Cambrian, surrounded by older formations.

it completely surrounds them. This distribution is not peculiar to the Cambrian, but is characteristic of most formations as compared with those of greater age. (2). The exposed areas of Cambrian in the Appalachian Mountains¹ occur in parallel or sub-

¹ See folios of the U. S. Geol. Surv.

parallel belts (Fig. 358). This is the result of (a) the folding to which the Cambrian and later strata of this region have been subject, and (b) the erosion which the folds have suffered. Fig. 362 will help to explain the repetition of outcrops. In this diagram, *A* represents pre-Cambrian strata, *C* represents the Cambrian, and *O*, *S*, *D*, and *C* the Ordovician, Silurian, Devonian, and Carboniferous systems, respectively. After the strata were folded, erosion cut the folds down. A fold which involves Cambrian beds, if truncated below the level of the bottom of these beds at their highest point, exposes two belts of Cambrian strata, one on either side of a pre-Cambrian axis, as represented in the left-hand part of the figure. If the truncation is at a level below the top and above the bottom of the Cambrian (right-hand side of Fig. 362), the strata of that system are exposed in a single belt along the crest of the fold. (3). In some places, Cambrian outcrops are surrounded by older formations. In such cases the Cambrian outcrops presumably represent remnants which have escaped erosion. They might occupy depressions in the surface of pre-Cambrian formations, or they might constitute hills (Fig. 363).

Width of outcrops. The most extensive continuous outcrops of the Cambrian (Fig. 358) are in Wisconsin; yet there the Upper



Fig. 364.—Diagram illustrating the influence of dip on the width of outcrop. The Cambrian beds, *C*, to the left have a much wider outcrop than the Cambrian beds to the right, though the thickness is the same.

Cambrian only is present, with a thickness of less than 1,000 feet, while in the Appalachian Mountains, where the system has an aggregate thickness of several thousand feet, it appears at the surface in narrow belts. That is, the outcrops are narrow in the east where the system is thick, and wide in the interior where it is thin. The explanation of this apparent anomaly is found primarily in the attitude of the strata. In Wisconsin they are nearly horizontal, while in the mountain regions, both east and west, they are

tilted, often at high angles. Where strata are vertical, the width of their outcrop on a horizontal surface is about the same as the thickness of the beds (Fig. 364); where they are nearly horizontal, as in the left-hand side of Fig. 364, the width of outcrop on a horizontal surface is much greater.

It is not to be inferred, however, that horizontal strata necessarily have a wide outcrop. The width of the outcrop is also in-



Fig. 365.— Diagram illustrating the effect of topography on the width of the outcrop.

fluenced by topography, as shown in Fig. 365. Here the horizontal stratum between *B* and *C* has about the same thickness as *C* of Fig. 364, but its outcrop is narrow. In general, the width of outcrop, so far as determined by topography, depends on the angle between the bedding-planes and the surface where the formation outcrops. The width of the outcrop decreases as this angle increases.

Changes in the Cambrian sediments since their deposition. The sediments of the Cambrian system have undergone more or less

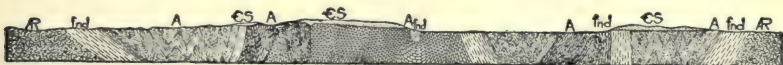


Fig. 366.— This figure represents a section in the Menominee region of northern Michigan, and shows the Potsdam sandstone, *CS*, in unconformity with older formations. (Van Hise, U. S. Geol. Surv.)



Fig. 367.— Section showing the relation of the Cambrian in the Appalachian Mountains. The strata are both folded and faulted. *E*, Cambrian; *O*, Ordovician; *S*, Silurian. Length of section, 13 miles. (Hayes, Cleveland (Tenn.) folio, U. S. Geol. Surv. Ordovician and Silurian not separated in the original.)

change since their deposition. In most regions, the gravels, sands, and muds have been compacted and cemented into conglomerates, sandstones, and shales respectively. In some places, the cementation of the sandstone has gone so far as to convert it into quartzite.

Over great areas in the interior (Missouri, Wisconsin, Texas, etc.) the strata still remain in horizontal or nearly horizontal position, while in other regions they have been tilted, folded, and faulted. Where close folding has taken place, the rocks have been more or less metamorphosed. In extreme cases the sandstones have been converted into quartz schists, the shales into slates and schists, and the limestones into marble. Fig. 361 shows the general position of the Cambrian strata (ϵ) over much of the interior, and Figs. 367

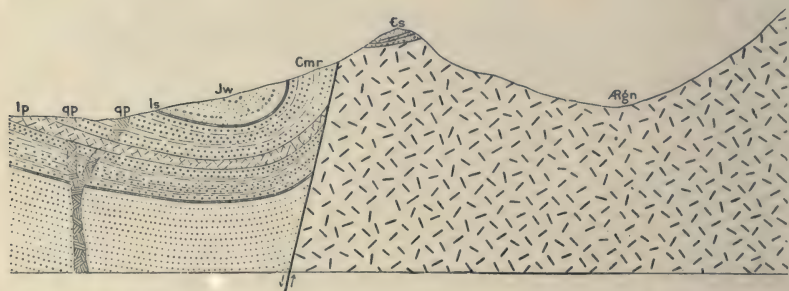


Fig. 368.—Section showing the relations of Cambrian and other formations at a point in Colorado a little north of Leadville. *Rgn*, Archean; ϵ s, Cambrian (Sawatch quartzite); *Cmr*, Carboniferous (Maroon formation); *Jw*, Jurassic (Wyoming formation); *lp* and *qp*, igneous rocks. (Emmons, U. S. Geol. Surv.)

and 368 illustrate their position and relations where they have been folded and faulted.

Close of the Cambrian. No physical changes of great importance seem to have marked the close of the Cambrian period in America. Nowhere in our continent, so far as now known, were mountains made at this time, and nowhere were great areas of sea-bottom converted into land, though local unconformities¹ between this system and the next record local changes in the sites of deposition.

In Other Continents

Europe.² In Europe, as in North America, wide-spread deformation before the beginning of the Cambrian converted large areas

¹ Cushing. Bull. Geol. Soc. Am., Vol. XIX, p. 155.

² The best summary, in English, of the Cambrian of Europe, is found in Geikie's Text-book of Geology, 4th ed., Vol. II.

of the present continent into land, and there is evidence that these lands, like those of America, were subjected to protracted erosion before the deposition of the Cambrian system, for it is generally unconformable on older strata.

The Cambrian formations of Europe, like those of America, are mainly clastic. A considerable portion of the material involved in them is coarse, and the strata are often ripple-marked, and affected by cross-bedding and by sun-cracks,—features which show that a large part of the Cambrian sediments were laid down in shallow water, and some of them where they were not continuously covered by water.

In Wales (Cambria), the country from which the system received its name, the system has a thickness of 12,000 feet or more. This great thickness is equalled or exceeded in Brittany. In Scandinavia, on the other hand, where Lower, Middle, and Upper Cambrian all are present, the aggregate thickness is sometimes no more than 400 feet. In western Russia also it is thin. These differences probably mean that sediments were being deposited in some places many times as rapidly as in others. They probably also mean that the sediments were sometimes spread over flats under shallow water and sometimes on shelving bottoms where the layers were inclined. The Middle Cambrian is much more wide-spread than the Lower or Upper, showing that changes in the relation of sea and land were in progress during the Cambrian period, shifting the areas of erosion and sedimentation.

The Cambrian strata of western Europe have been much folded since their deposition. In central and eastern Europe, on the other hand, they are essentially horizontal. Beds of clay which are still plastic, and beds of sand which are still uncemented, are here found in the system.

No geographic change of great importance seems to have marked the close of the Cambrian. In this respect, as in some others, the Cambrian histories of Europe and North America correspond.

Other countries. Cambrian rocks occur in various parts of Siberia, China, India, Australia, and Tasmania, and in the north-western part of Argentina, but their distribution outside of North America and Europe is but poorly known.

Glacial formations. (1) In the vicinity of Varanger fiord, in northern Norway, Lat. $70^{\circ} 8' N.$, there is a bed of boulder-bearing rock (the *Gaisa* beds)¹ resting on a smoothed and striated pavement of distinctive glacial type. The Gaisa beds rest upon the eroded surface of a crystalline terrane, and have been thought to belong to the oldest part of the Cambrian system, or to antedate it. (2) Recent exploration in China² has shown the existence, on the Yangtse

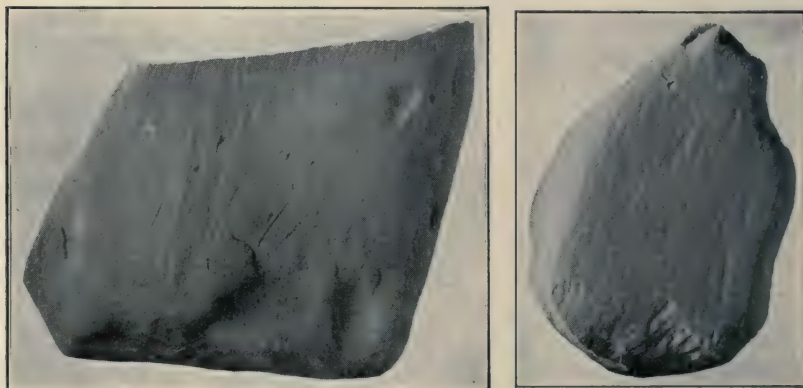


Fig. 369.— Glaciated stones from the glacial beds at the base of the Cambrian in China. (Willis, Carnegie Institution.)

River, in latitude 30° , of a thick formation (170 feet) of boulder-bearing rock of glacial origin, containing many striated boulders of diverse sorts of rock (Fig. 369). The glacial formation here lies at the base of the Paleozoic, and beneath the series that carries the Cambrian trilobites.

Glacial formations of about the same age have been found in Australia, and perhaps in South Africa.³ The most probable interpretation, with present knowledge, is that these boulder-bearing formations of Norway, China, and Australia (Fig. 370) belong either to the transition period that accompanied and followed

¹ Reusch, Norges geologiske Undersoegelse: Det nordlige Norges Geologi, 1891. Also Strahan, Quar. Jour. Geol. Soc., Vol. LIII, 1897, pp. 137-146.

² Willis, Researches in China, Vol. II.

³ David, Report of International Geological Congress at Mexico, 1907; and Howchin Quar. Jour. Geol. Soc., Vol. LXIV, p. 234, 1908.

the deformation that closed the Proterozoic, or to the opening stages of the Paleozoic, previous to the demonstrated Cambrian. The profound climatic significance of these glacial formations is



Fig. 370.— Section showing glacial beds, South Australia.

obvious. The testimony of Cambrian fossils, on the other hand, implies nearly uniform climatic conditions throughout all regions where fossils have been found, and the wide spread of the sea



Fig. 371.— A glacial boulder from the Cambrian till of Petersburg, South Australia. (Howchin.)

during the later part of the period would seem to point to oceanic, rather than continental climates at that time.

Duration of the Cambrian Period

There is no way of making a reliable estimate of the duration of the Cambrian period. The destruction and the removal to the sea of such large volumes of rock as are represented by the sediments of the Cambrian required a very long period of time; but since there is no standard rate at which any sort of sediment is known to

accumulate, this long period cannot be reduced to years. It has been estimated that limestone sometimes forms at some such rate as one foot per century. In some parts of the West there are 6,000 feet of limestone, besides thick bodies of fragmental rock. At the above rate of accumulation, the 6,000 feet of limestone would call for a period of 600,000 years, and if time be allowed for the other formations of the same region, the period would be greatly lengthened. It should be remembered, however, that while one foot per century may be a rate at which limestone sometimes accumulates, it does not follow that it is the rate at which the Cambrian limestones were formed. The data on which this estimated rate is based are believed to give too high, rather than too low a rate, and a less rapid accumulation would mean a correspondingly longer period of time.

Many estimates of geological time, based on various data, have been attempted.¹ These estimates, so far as applied to the Cambrian, generally assign to that period a duration of 1,000,000 to 3,000,000 years. It should be distinctly borne in mind, however, that the chief value of these figures is to give emphasis to the fact that the period was one of great duration.

THE LIFE OF THE CAMBRIAN

Perhaps no single event in the history of the earth possesses greater interest than the first appearance of life; but the date of its advent is not known. There is good evidence that life existed before the close of the Archeozoic era, and under the accretion hypothesis, it is not improbable that its beginning antedated, by a long period, even the oldest accessible Archean formations. If so, it is quite beyond hope that the earliest forms of life will ever be known from its relics. The evidences of plants and animals in the Proterozoic era are so indirect, obscure, or meager that they give but a very inadequate conception of the life before the Cambrian period. The information which the imperfect fossils give, indicates that they do not tell even the main part of the story of Proterozoic

¹ For a general discussion of this matter, see Williams' *Geological Biology*, Chap. II.

life, for the life represented by the fossils could not have lived without other life not represented.

The Cambrian is the oldest system in which there is a reasonably adequate record of life, and even here the record is far from complete. The animal kingdom is fairly well represented among the fossils, but plant remains are barely identifiable.

The scantiness of plant fossils. The existence of plants in the Cambrian period would perhaps be doubted were it not known that all animals depend on them, directly or indirectly, for food. It must be supposed, therefore, that plants abounded. The inadaptability of the lower plants to fossilization is doubtless the chief explanation of their poor representation among the Cambrian fossils. Reasons of a physical nature have been given previously for thinking that the surface of the land was clothed with some kind of vegetation. Yet there are no identifiable traces of land-plants, and but obscure impressions of sea-plants. The lesson taught is the extreme imperfection of the fossil record.

The Animal Fossils

Every great division of the animal kingdom, except the vertebrate, had its representatives in Cambrian times. The *Arthropoda* (p. 945) were represented by crustaceans; the *Mollusca*, by gastropods, pteropods, and pelecypods; the *Molluscoidea*, by brachiopods; the *Vermes*, by annelids; the *Echinodermata*, by cystoids; the *Coelenterata*, by graptolites, medusæ, and corals; the *Porifera*, by sponges, and the *Protozoa*, by rhizopods. All the representatives of these groups among the Cambrian fossils appear to be marine. Of land animals there are no traces, but this does not prove that land animals did not exist. Though no vertebrate remains have yet been found, it would be rash to assume that none of them were in existence.

Arthropoda. Of the *Arthropoda*, crustaceans (represented now by crayfish, crabs, etc.) only have been found in the Cambrian strata. Their representatives were trilobites and entomostracans. The *trilobites* were easily the most distinguished forms of life in the Cambrian seas. They were not only the highest in organization, but they were the most characteristic of the period. Their

successive genera best distinguish its successive stages, and their distribution is a chief means of correlating the formations of different continents, and of different provinces of the same continent, as previously set forth (p. 481). They have long been extinct. Figs. 359 and 372 show their three longitudinal lobes (whence their name), and their three transverse divisions, head, thorax, and caudal shield. The trilobites were well advanced in the scale of development, possessing nearly all the anatomical systems and

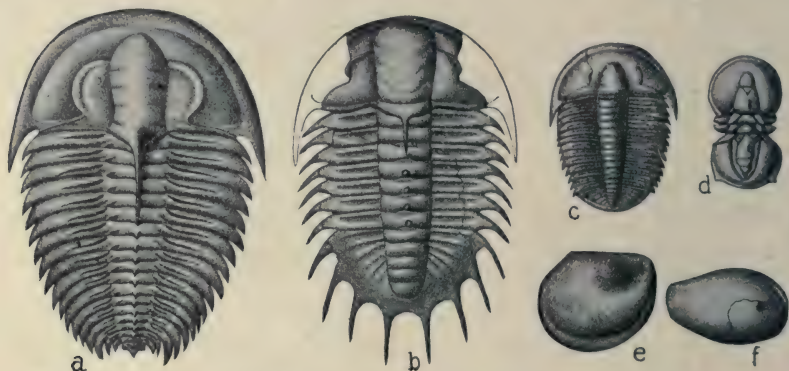


Fig. 372.—*Cambrian Crustacea*: *a*, *Holmia* (*Olenellus*) *broggeri* Walcott, a characteristic trilobite of the Lower Cambrian; *b*, *Olenoides curticei* Walcott, a Middle Cambrian trilobite; *c*, *Ptycoparia kingi* Meek, a Middle Cambrian trilobite; *d*, *Agnostus interstrictus* White, a Middle Cambrian trilobite; *e*, *Aristozoe rotundata* Walcott, a Cambrian phyllocarid; *f*, *Leperditia dermatoides* Walcott, a Cambrian ostracode.

physiological functions of modern crustaceans. Perhaps their compound eyes, formed of many eyelets, are the best index of their development. In this and succeeding periods, the number of eyelets in the trilobites' eyes ranged from a score to several thousands. Some of the Cambrian trilobites, however, had no eyes, while others possessed abortive rudiments, implying that their ancestors had possessed eyes. The acquisition and abortion of so important an organ seems to indicate variation in the conditions of life. This may mean no more than migration to deep dark waters, or the habit of burrowing in the mud, where eyes became useless. The eyes were often slightly raised on crescentic lobes, with the convex face

outwards. In later epochs, these crescents became more and more curved, extending the sweep of vision fore and aft, to the trilobite's obvious advantage.

The upper surface of the body was ornamented variously with granules, spines, and other markings, the significance of which is little understood. These ornamentations varied as time went on, increasing, in general, until after the climax of the trilobites had been passed. Trilobites possessed a row of slender articulated

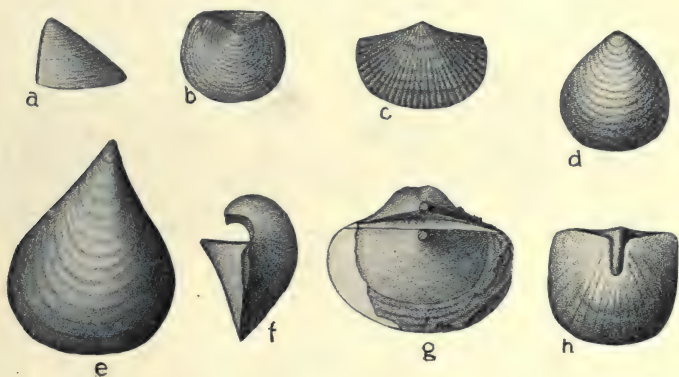


Fig. 373.—*Cambrian Brachiopods*: *a* and *b*, *Acrotreta gemma* Billings, a brachiopod ranging from the Lower to the Upper Cambrian, summit and side views of the ventral valve; *c*, *Billingsella transversa* Walcott, a pedicle or ventral valve of a hinged brachiopod of the Lower Cambrian; *d* and *e*, *Lingulepis piniformis* Owen, views of the two valves; *f*, and *g*, *Kutorgina cingulata* Billings, side and dorsal or brachial views; *h*, *Billingsella coloradoensis* (Shum.).

limbs on either side, and delicate filaments which served the function of respiratory organs. The nature of the limbs indicates that the trilobites both walked and swam. They possessed antennæ which doubtless served as organs of touch, and they moulted the shell at successive stages of growth, like modern crabs. Omitting further details, it is to be observed that, at this early day, a highly complex, well-differentiated organization had been acquired, possessing nearly all the organs and functions of arthropods of the present day.

Molluscoidea. This branch was well represented by *brachiopods* (lamp-shells, Fig. 373). In geological importance, the brachiopods

of the period were second to trilobites only; but unlike the trilobites, brachiopods still live, and are conspicuous representatives of stability and persistence. Though the species and most of the genera have changed, the class as a whole has been but slightly modified since the Cambrian period. Then, as now, the valves of one division of the group were hinged, while those of another were not. One division formed shells of calcium phosphate, and another of calcium carbonate.

Mollusca. *Cephalopods* (chambered shells), the highest class of mollusks, are found in the uppermost beds of the Cambrian. As



Fig. 374.—*Cambrian Mollusks*: *a*, *Hyolithes americanus* Billings, a Lower Cambrian pteropod; *b*, *Fordilla troyensis* Barrande, a Lower Cambrian pelecypod; *c*, *Stenotheca rugosa* Hall, a capulid gastropod of the Lower Cambrian; *d*, *Trochus saratogensis* Walcott, a Cambrian gastropod with well-developed spire; *e*, *Platyceras primævum* Billings, a Lower Cambrian gastropod; *f*, *Ophileta primordialis* Winchell, an Upper Cambrian gastropod.

they were even then highly developed, there is little doubt that the class had passed through a long history before the latter part of the period.¹ *Pelecypods* (bivalves, *b*, Fig. 374) lived even in the early part of the period, though their remains are not abundant. *Gastropods* (univalves, *c*, *d*, *e*, Fig. 374) were rather plentiful throughout the period. The early forms are chiefly of the low conical type, while more amply coiled and spiral forms became common later. The close resemblance of some of them to modern gastropods is worthy of note.

¹Ulrich would refer the beds containing the Cephalopods to the *Ozarkian*, a system which he would make to include the upper part of the Cambrian and the lower part of the Ordovician, as usually classified.

Vermes and echinodermata. Sea worms left evidence of their abundance by borings, tracks, etc. (Fig. 375). A few *cystoids*, the forerunners of the beautiful crinoids (stone lilies) were present, but fossil crinoids have not been found.

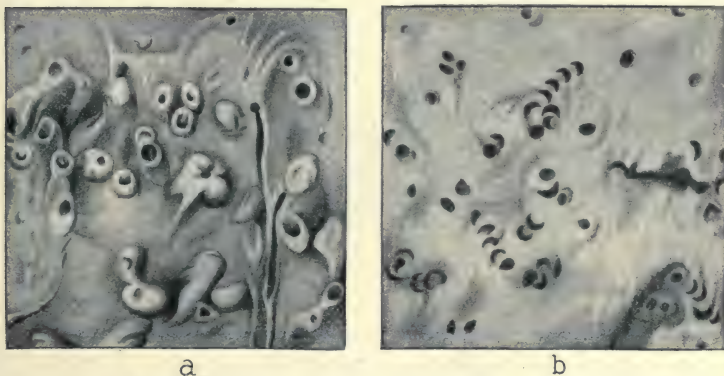


Fig. 375.— *Cambrian Vermes*: borings and trails. *a*, a natural surface of sandstone seen from above, showing annelid borings, with mounds of sand heaped about their mouths and with trails leading away from some of them; *b*, a horizontal section, showing perfect borings, as well as abandoned borings whose sides have been forced in during the formation of new borings, giving a crescentic cross-section. Although the animal is not shown, the name *Arenicolites woodi* Whitfield, is assigned to it.

Coelenterata. The coelenterates were represented by *hydrozoa* (graptolites and medusæ) and *anthozoa*. The eccentric freaks of fossilization are nowhere better illustrated than here. Relics of graptolites, among the most delicate of animal forms, and of medusæ, among the softest of animals, were preserved, while some much less easily destroyed forms left scant record of themselves. The *graptolites*, now extinct, were slender, plume-like organisms, consisting of a series of indurated cells, in which the individual zoöids lived, attached to a common slender axis which united the colony. The whole colony appears to have floated free in the sea (Fig. 376, *e*). The secret of their preservation probably lies in the fact that, being floating forms, they often settled in quiet and rather deep waters off-shore, where fine silts accumulated, and where the

conditions were favorable for burial without destruction. The most singular case of fossilization is the preservation of traces of *jelly-fish*, or at least of what are so identified. These are illustrated in Fig. 376, *c* and *d*. Their impressions are found in the Lower Cambrian. Obscure fossils of corals are present (Fig. 376, *a* and *b*), the forms of which resemble sponges so much that they were long

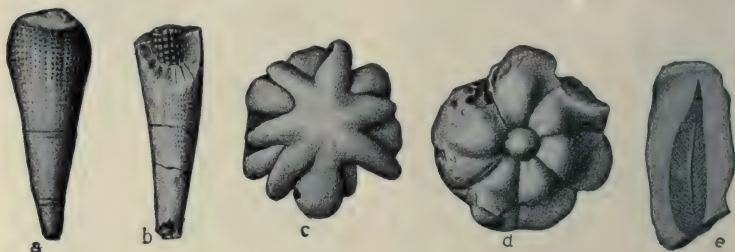


Fig. 376.—*Cambrian Cœlenterata*: supposed corals, medusæ, and graptolites. *a* and *b*, *Archæocyathus rensselaëricus* Ford, a problematic fossil referred by some paleontologists to sponges, and by others to corals; *c* and *d*, *Brooksella alternata* Walcott, supposed casts of the gastric cavities of medusæ; *c*, a supposed exumbrella in which the interumbrella lobes are a prominent feature; *d*, a view of a supposed umbrella with six lobes and a depression over the central stomach; *e*, *Phyllograptus* (?) *cambrensis* Walcott, the hydrosoma of a graptolite.

regarded as such. Corals seem to have been more abundant in some other parts of the world than in North America.¹

Lower types. *Sponges* were present in some abundance throughout the period. It is probable that many of the low, simple forms classed as *protozoans* existed, but only a few identifiable forms have been found.

Implied life. The existence of so much animal life implies much vegetable life to supply the necessary food, as heretofore noted. Furthermore, various characteristics of the fossils suggest the presence of animals not known from fossils. A large percentage of the known Cambrian animals were provided with shells, tests, plates, or other forms of hard coverings. In the main, these appear to have been protective devices, and imply enemies or combative rivals against which protection was needed. Perhaps the

¹ Howchin, Quar. Jour. Geol. Soc. Vol. LXIV, p. 237.

most significant feature of the protective devices lies in the fact that they are usually of the same type as those possessed by the similar animals of later times. The shells of the gastropods, pelecypods, and brachiopods differ from those of to-day in minor features only. The coverings of the trilobites were much like those of their living relatives, and much the same may be said of nearly every form. If there had been a radical change in the character of their enemies or rivals, we might expect some notable change in the defensive devices. It is a natural inference, therefore, that the conflicts of life in the Cambrian seas were similar to those of the present time. The inference may be pushed a step further, and the deduction drawn that the conflicts which led to the evolution of the defensive devices were much like those throughout the period of their retention.

Stage of evolution represented. What stage of advancement in the development of life had been already attained by the beginning of the Cambrian period? Do the fossils of the system indicate that the life of the period was primitive, or do they imply that it had advanced far beyond primitive forms? The answer to these questions is to be sought (1) in an estimate of the degree of development of the various organic structures and functions, and (2) by the amount of divergence of the animal types.

(1) For comparison it may be assumed that the primitive forms of life were as simple as the simplest existing forms. There are multitudes of plants and animals that consist of a single cell, and if these are taken as representing the nearest existing approach to primitive forms, how far had the Cambrian life advanced beyond them?

We are not left entirely to the presumption that the earliest forms of animal life were much simpler than those of the Cambrian, for the stages of development of the young of certain of the Cambrian animals reveal something of their ancestral history. It is a well-established law of embryology that animals, in the early stages of their development, pass through a succession of changes in which their structure resembles that which their ancestors had in their maturity; in other words, the individual history of any animal is an epitome of the history of its ancestors. Now the

Cambrian trilobites are known to have passed through a series of remarkable changes after the individuals had developed far enough to be fossilized, and it is inferred they passed through other stages previously. There is, therefore, specific ground for believing that they had a long line of ancestors.

On the anatomical and physiological side, it is clear that nearly or quite all the fundamental organs had been developed. There were skeletal systems of several forms, muscular systems, nervous systems of high development, as implied by eyes and other sense-organs, devices for capturing and ingesting food, organs of digestion, secretion, excretion, and respiration; in short, practically all the great anatomical and physiological systems now possessed by animals. The Cambrian animals had acquired the various habits of life possessed by existing animals of their kind, as well as the various modes of preserving their lives.

(2) The studies of recent decades have convinced investigators that later forms of life were derived from earlier ones by processes of evolution, the exact method of which is not altogether understood; but the fact of derivation is not now regarded as an open question. As the various forms developed and diverged from a common ancestral stock, many of the intermediate forms disappeared, and thus the diverging forms became somewhat widely separated. By continued divergence, with the loss of intermediate types, a more and more discontinuous series of forms was developed, and those branches which lived on became more and more distinct. The process was not unlike the evolution of a tree-top, in which the dying out of most of the interior branches leaves a few great limbs which bear the more numerous and more recent branches, while these in turn bear the uppermost and outermost twigs which represent the living phase. In some such way, it is thought that the existing divergence of organisms into kingdoms, branches, classes, orders, families, genera, species, and varieties came to be established.

If it is assumed that the whole system of living things has been derived from a common primitive form or from a few primitive forms, a comparison of the primitive state with the degree to which divergence had gone in the Cambrian times will give some im-

pression of the amount of evolution already accomplished. If to this be added a comparison between the Cambrian life and that of the present time, an estimate of the relative amount of evolution before and since the Cambrian period may be made.

It is to be noted that not only were all the animal sub-kingsdoms, save perhaps the vertebrate, present, but that, in many of them, the forms had come to have so nearly the aspect of living forms that the classes and some orders are readily recognized. *The initiation and divergence of the structures and types that preceded the Cambrian stage mean much more in the way of evolution, than all the evolution of later times.* Formulated in numerical terms, we may perhaps say that 60 to 90 per cent of the evolution represented by the life of today, had been accomplished in pre-Cambrian times.

Mental development. The wars of the Cambrian animals, implied by their weapons of offense and defense, can scarcely have been unaccompanied by some notable measure of mental development, however the nature of such development may be interpreted. That the trilobites sought their food or pursued their prey by sight, and were guided by touch, is implied by their eyes and antennæ, and it is difficult to conceive of functional senses without the mental processes that usually attend pursuit and capture.

Ecological adaptations. The distribution of the Cambrian fossils indicates that then, as since, there was an adaptation of life to its physical environment. There seem to have been zones of shore life, off-shore life, and deep-sea life, although the evidence of the last is scant. These variations must be taken into account in the comparison and correlation of faunas, for considerable geographic differences may occur among faunas which were strictly contemporaneous.

Zoölogical provinces. The assemblages of the life of the period seem to have varied in a broader way, giving rise to zoölogical provinces. It is probable that the leading factors in the development of these provinces were barriers that isolated, or partially isolated, certain portions of the sea from other portions. The separation must have reached such a degree as to cause the life of each area to develop along its own lines, in more or less independence of the evolution of other regions.

The early faunas of the Cambrian were somewhat provincial in nature, but toward the close of the period, as the seas spread over the continents, there was a marked tendency toward cosmopolitanism. The impression must not be gained that life was everywhere the same at a given stage. There was probably less variation geographically, during most geologic periods, than there is to-day, though it is not certain that this was true of all past epochs. It is improbable that there was ever uniformity over the whole globe.

The Succession of Faunas

Under the doctrine of evolution, it is presumed that the life of every past stage has grown out of that which immediately preceded it, and that it has merged into that which immediately followed it. It is usually assumed that if no exceptional influences affected the process, there was a continuous series of slow changes without sharp lines of demarkation. If this conception were realized in fact, it would be less appropriate to speak of a succession of faunas than of one continuous ever-changing fauna. It is not yet demonstrated, however, that evolution proceeded solely by very slight changes coming in from generation to generation. It may have proceeded by distinct and abrupt changes.¹ This doctrine, as now held, does not maintain that a whole fauna would be likely to change into a different fauna abruptly, but merely that new species might arise in it abruptly. Irrespective of this or any other specific hypothesis, it is to be noted that the geological record, as now known, does not show complete gradations from one species into another. In some cases there is a close approximation to a graded series from one species to another, but the steps of the gradation are not sufficiently close and definite to decide between evolution by an infinite number of small changes, and a smaller number of greater changes.

If we turn from species to faunas, it is obvious that a more general point of view must be taken. Observation shows that in some cases one fauna graduates into the succeeding one, while in

¹ DeVries *Die Mutationstheorie*, 1903. See also Bateson's *Materials for the Study of Variation*, 1894; and W. B. Scott, *On Variations and Mutations*, *Am. Jour. Sci.*, 1894, p. 355.

other cases the change appears to be abrupt. If the progress of life the world over could be studied as a unit, it would probably appear that there was a nearly perfect gradation of the life of one stage into that of the next. This gradation probably took place more rapidly at some times than at others, and it is quite certain that some forms changed much more rapidly than others. But when we limit our study to the succession of faunas on any one continent, or to any one province, it is evident that the progress of evolution in the region studied was interrupted by physical changes which affected the depth, temperature, or clarity of the water, and the nature of the bottom, and that these changes brought about variations in the character and distribution of life. Out of these local influences superposed on the general progress of life, there came to be rather definite times of notable change, between which the faunas retained a rather constant character, though always undergoing some modification. Where the faunal change in a conformable series is abrupt, and there is no evidence of a hiatus in the record, the explanation is usually to be sought in migration, as when a new fauna came in from some other region, overwhelming the old fauna. The whole process is closely analogous to the well-known succession of human races brought about by the migrations of man.

In the study of faunal progress, therefore, there is occasion to recognize (1) rather abrupt changes brought about by overwhelming invasions; (2) less abrupt changes brought about by the more gradual ingress of outside species, and the gradual comingling of the immigrants with the resident species; (3) very gradual changes due to the slow evolution of resident species when not much affected by immigration or by physical changes; and (4) more rapid evolution due to profound changes in the physical conditions or to other agencies less well understood.

The abrupt appearance of the Cambrian fauna. The explanation of the apparent suddenness of the appearance of the Cambrian fauna is one of the open questions of geology. In a general way, it may be said that older formations have been subjected to metamorphism, and that this tended to destroy their fossils; but this suggestion is not altogether adequate, for some of the older formations are not greatly changed, and seem quite suitable for the pres-

ervation of fossils. Furthermore, fossils are sometimes retained in later formations that have been much disturbed and altered. It is also true that some later formations which seem well suited to receiving and retaining organic impressions are devoid of them. Geologists are inclined to refer the scantiness of pre-Cambrian fossils, and hence the *apparent* abruptness of the introduction of the Cambrian fauna, to unfavorable conditions for fossilization in pre-Cambrian time, combined with subsequent changes in the rock. This makes the abruptness a matter of record, rather than a matter of fact.

Map Work. The following folios of the U. S. Geological Survey furnish good maps for the study of the stratigraphy and the stratigraphic relations of the Cambrian system in different parts of the United States. The texts of the folios give some account of the physical history of the several regions: *Alabama*, Gadsden; *Arizona*, Clifton; *Colorado*, Anthracite-Crested Butte; *Georgia*, Rome; *Maine*, Penobscot Bay; *Massachusetts*, Holyoke; *Michigan*, Menominee; *Montana*, Little Belt, Fort Benton; *New Jersey*, Franklin Furnace; *North Carolina*, Mount Mitchell, Nantahala, and Pisgah; *Oklahoma*, Tishomingo; *Tennessee*, Maynardville, and Morristown; *Utah*, Tintic; *Virginia-West Virginia*, Bristol, Harper's Ferry, Tazewell; *Wyoming*, Absaroka (Crandall Sheet), Bald Mountain-Dayton, Cloud Peak-Fort McKinney, and Sundance.

CHAPTER XVII

THE ORDOVICIAN (LOWER SILURIAN) PERIOD

FORMATIONS AND PHYSICAL HISTORY

The general conformity¹ between the Cambrian and Ordovician systems shows that no considerable physical change took place in the relations of land and water in North America at the close of the Cambrian period. At the opening of the Ordovician, therefore, as at the close of the Cambrian, an epicontinental sea stood over much of the continent.

Sedimentation During the Ordovician Period

The conditions of sedimentation during the Ordovician period were somewhat different from those of the Cambrian. All the common processes of weathering were operative on such lands as still existed, wasting the rocks and preparing sediment for removal to the sea; but the small area of land within North America yielded but little sediment, and during much of the period the deposition of land-derived sediment was confined to littoral tracts. Farther from land the shells, skeletons, and other secretions of marine animals and plants were accumulating, making limestone. Since the land areas of the period were of various sizes, of various sorts of rock, and presumably of various heights, it is probable that conditions existed for the deposition of all sorts of clastic sediments about their borders, and for their deposition at very different rates. Sedimentation was doubtless more rapid near the larger and higher land masses than about the smaller and lower ones, and more rapid on that side of any land towards which the larger part of its drainage was directed.

The sedimentary formations of the Ordovician period are in

¹ There are local unconformities between these systems, as in some parts of New York, and they may be more wide-spread than has been supposed.

keeping with these general principles. Adjacent to the broad, shallow arm of the ocean which covered the larger part of the Mississippi basin (Fig. 358) there appear to have been no sources of abundant sediments during most of the period. Along the western base of Appalachia, mud, sand, and gravel, washed down from the land, were being deposited. The coarser materials were left nearer the land, while the finer were carried farther out. Alternating beds of coarse and fine sediment indicate either (1) that the adjoining land was higher at some times than at others, or (2) that the climatic conditions or (3) the vegetal covering changed, or (4) that waves and currents varied in their effectiveness.

The sediments deposited at the same time in Newfoundland, in the northeastern parts of Canada, and in the Ottawa basin, were largely of limestone, indicating the absence of abundant debris from land in these regions. About the isolated land masses farther west, sand and mud, to become sandstone and shale later, were in process of accumulation; but the sources of material appropriate for such formations were not extensive, and the formations themselves are correspondingly limited. Conditions for the formation of limestone prevailed widely in the epicontinental sea. Plants and animals secreting calcium carbonate may have been no more abundant far from land than near it, but away from shore their shells, etc., were probably more abundant *relative to the sediments derived from the land*. The occasional variations from limestone to shale or sandstone in the interior of the continent show that physical conditions were not altogether constant.

But even during those intervals when the land was so low as not to yield abundant sediments, preparation was making for future formations of clastic rock. The formations of the land were undergoing decay, even though the products of decay were not removed. Under these conditions, thick mantles of residual earths accumulate, representing the excess of rock decay over transportation. During such periods of rock decay a large amount of disintegrated material is made ready for removal when uplift of the land rejuvenates the streams.

The development of the Ordovician system meant the destruction of an equivalent body of older rock. The old material which

entered into the new system, derived from all preceding formations so situated as to be exposed to erosion, was brought from the land by streams, worn from its shores by waves, or blown to the sea by winds; and where terrigenous sediments failed, or where they were relatively unimportant, the secretions of the animals and plants accumulated, giving rise to sedimentary rocks of organic origin. Even these had their ultimate source in the older formations, for the mineral matter extracted from the sea to make the shells had been dissolved from older formations during the process of their decay, and brought to the sea in solution, often by the same streams which brought the mud in suspension.

It is probable that the larger part of the ocean basins was continuously submerged during the Ordovician, as during earlier periods, and that in them the Ordovician strata overlie those of Cambrian age conformably. Though nothing can be known directly of the Ordovician system beneath the sea, it is important, in the conception of the system as a whole, to remember that it probably underlies most of the oceans as well as many of the younger formations of the land, and that its exposed margin is but a trivial fraction of its total area.

Sections of the Ordovician

The New York section. The Ordovician system of North America was first studied carefully in New York, and the section of that State is, in some measure, the standard to which others are referred. The system in New York is now divided as follows:

Ordovician	Upper Ordovician (or Cincinnati)	{ Richmond beds ¹ (in Ohio and Indiana) Lorraine beds Utica shales
	Middle Ordovician (or Mohawkian)	{ Trenton limestone Black River limestone Lowville limestone
	Lower Ordovician (or Canadian)	{ Chazy limestone Beekmantown limestone (calciferous)

¹ Question has recently been raised as to the propriety of including the Richmond beds in the Ordovician. It has been suggested that they are perhaps the equivalent of the Medina, and if so they belong with the succeeding system. Hartnagle, N. Y. State Mus. Bull. 107, 1907. In Illinois, beds of Richmond age are unconformable on the underlying Ordovician. Weller, Jour. of Geol., Vol. XV, p. 519; and Savage, Am. Jour. Geol., Vol. 125, p. 431, 1908.

Other sections. The classification of New York is not applicable in detail to the system in other parts of the continent. In Wisconsin, Iowa, and Minnesota, for example, the formations commonly recognized, numbered in the order of age, are as follows:

Upper Ordovician	5. Hudson River ¹ (Maquoketa) shale
Middle Ordovician	{ 4. Galena limestone
	{ 3. Trenton limestone
Lower Ordovician	{ 2. St. Peters sandstone
	{ 1. Lower Magnesian limestone

It can hardly be affirmed that any one of these formations is the exact equivalent of any one in New York.

In the Appalachian Mountains² of Tennessee, a series of limestone or dolomite beds (Knox, Chickamauga, etc.), the lowest not distinctly marked off from the Cambrian below, is followed by a series of clastic beds (Sevier shale, Bays sandstone, etc.).³ The exact relations of these formations to those of New York and to those of the upper Mississippi basin have not been determined, and since the strata between Tennessee and these localities are concealed for the most part, the relations must remain unknown, except in so far as the fossils may reveal them. The section of Tennessee does not correspond in details, with that of other parts of the Appalachian belt.

General conditions in the eastern part of the continent. It is worthy of note that in mid-Ordovician time, limestone was forming from New England on the east, to Georgian Bay on the northwest, to Oklahoma and Texas on the southwest, and Alabama on the south. Limestone was forming also in much of the west. At no previous epoch was there anything like such wide-spread deposition of limestone within the limits of our continent. The explanation of this condition of things has been suggested already (p. 508). It

¹ It is now held by some that a portion at least of the Hudson River shale of the Mississippi basin (Maquoketa of Iowa, Illinois, etc.) is the equivalent of the Richmond beds farther east. Its classification with the Ordovician is therefore subject to question. (See footnote, p. 508).

² For local details in the Appalachians, see the folios of the U. S. Geol. Surv. On the maps of the folios, the Ordovician is classed with the Silurian under the latter name. The text of the folios frequently distinguishes between the Lower Silurian (Ordovician) and the Upper Silurian (Silurian).

³ The subdivisions mentioned here are those of the Maynardsville, Tenn., folio, U. S. Geol. Surv.

is perhaps equally worthy of note that in the latter part of the period, mud (now shale) was deposited over an almost equally extensive area. This may mean either that the lands were so elevated as to allow the streams to carry more sediment to the sea, or that conditions favored the transportation of mud farther from shore than formerly, or both. Associated with the Upper Ordo-



Fig. 377.—Trenton Falls, Trenton, N. Y. The locality whence the Trenton formation derived its name. (Darton, U. S. Geol. Surv.)

vician shales, there are considerable bodies of limestone in some places, and of sandstone in others. All the Ordovician formations of the interior and the east bear within themselves evidence of shallow water origin.

Western sections. In the Great Plains, the Ordovician system appears at the surface but rarely, though it probably underlies the younger formations. West of the Great Plains, the system is present generally, and the sections are somewhat simpler than in the interior or the east. As farther east, limestone is a conspicuous part of the system here.

Igneous rocks. Igneous rocks of Ordovician age attain little importance in North America. Their general absence is in harmony with the quiet which characterized the period.

General Conditions and Relations of the Ordovician System

Position of beds. As originally deposited, the Ordovician beds probably dipped away from such lands as then existed. Thus on the south side of the land of northern Wisconsin (Fig. 382), the Ordovician sediments must have dipped slightly to the south, and on the east and west sides, to the east and west respectively. The same relations held about every land area. Over great areas in the interior, this original and simple plan of stratigraphy has been but little modified (Fig. 378).

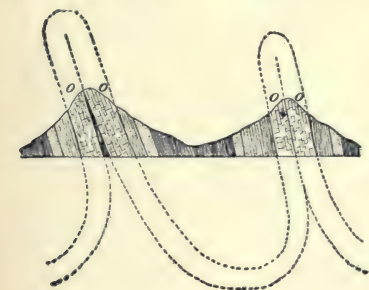


Fig. 381.—Section showing the position and relations of the Ordovician beds in the mountains of Arkansas. Length of section, about $1\frac{1}{2}$ miles. (Penrose, Ark. Geol. Surv.)

In other regions, deformation of the strata has completely changed their original positions. Thus in the Appalachian Mountains, where the sediments were derived principally from the land to the east, and where the beds doubtless had a slight dip to the west at the time of deposition, they now dip in various directions and at various angles, as the result of folding. Faulting has complicated their structure still further (Figs. 379 and 380). The strata are in similar

positions in some parts of Arkansas (Fig. 381), Oklahoma, and the various mountain ranges of the west.

Condition of the formations. The sediments have undergone more or less alteration since their deposition. In some places the changes have been slight, and in others great. The larger part of the Ordovician sands are now in the condition of sandstone, the larger part of the muds in the condition of shale, and most of the limestone is still essentially non-metamorphic. But where dynamic action has been great and where the original position of the strata has

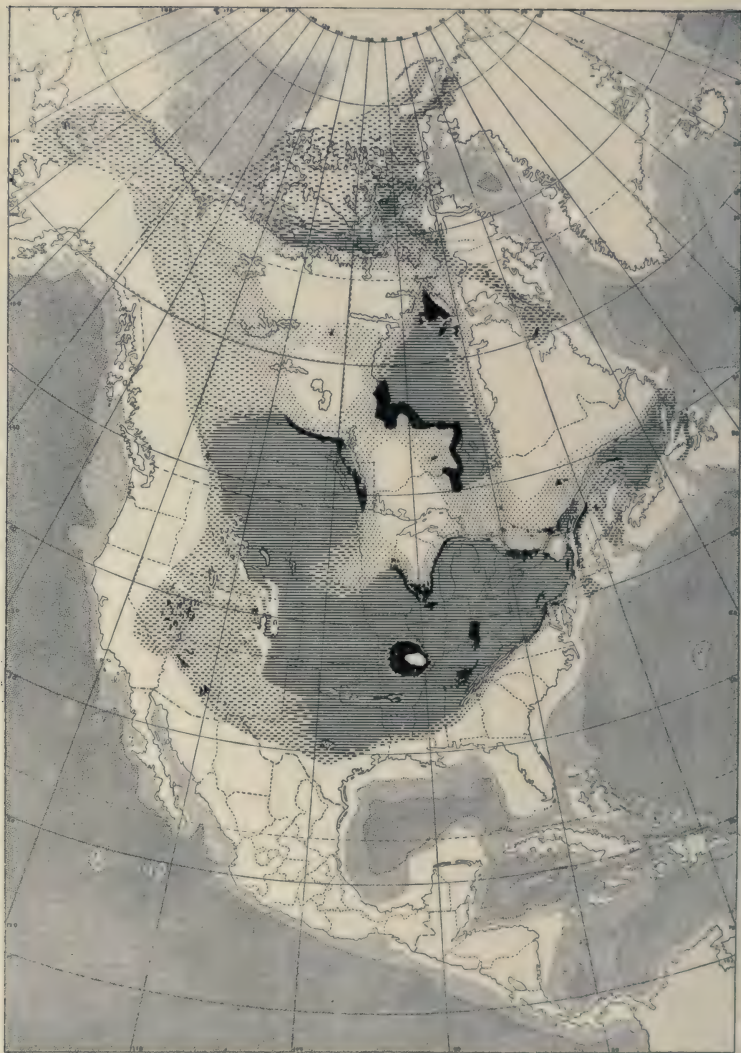


Fig. 382.— Map showing the general condition of the North American continent in Mid-Ordovician (Trenton) time. The black portions represent areas where the Middle Ordovician beds appear at the surface. These areas so nearly correspond with the areas where the Ordovician system as a whole appears at the surface, that no serious error is involved if the black areas be interpreted as Ordovician. The various conventions of the map are the same as in Fig. 358, p. 477.

been greatly changed, the changes in the rock have been greater.¹ Thus in the Taconic Mountains (southeastern New York and southwestern New England), the limestone is mainly in the condition of marble, the sandstone and quartzite have been largely changed to quartz schist, and the shales to slate and schist. Metamorphic rocks of Ordovician age are known also in some parts of the Piedmont plateau.

Thickness. The rocks of all systems vary greatly in thickness, and the Ordovician system is no exception. In the Appalachian Mountains it is to be measured by thousands of feet, while in the interior it is to be measured by hundreds instead. In Wisconsin and Iowa, where sedimentation seems to have been interrupted but little from the beginning of the period to its end, the aggregate thickness is rarely 700 feet.

Width and position of outcrops. In the interior, where the system is relatively thin, it sometimes appears at the surface in relatively wide belts or areas (Fig. 382), while in the eastern mountains, where it is thick, it appears at the surface in a succession of narrow and parallel belts (p. 488).

Close of the Ordovician Period

The close of the period was marked by geographic changes of more importance than those at its beginning. The greatest change was the withdrawal of the epicontinental waters from a large part of North America, converting extensive stretches of shallow-sea bottom into land. The cause of this change may have been the sinking of the ocean bottoms and the drawing off of the epicontinental waters. The altitude of this new land must have been slight or its exposure brief, for it suffered little erosion before much of it was again submerged and covered by sediments of later age. It is indeed the wide-spread absence of the lower part of the Silurian system (p. 536), rather than a pronounced stratigraphic unconformity between it and the Ordovician, which indicates the

¹ See, for example, the New York City, Holyoke (Mass.-Conn.), and Hawley (Mass.) folios, U. S. Geol. Surv. Compare with folios of (1) the Appalachian Mountains, (2) the interior, and (3) the western part of the United States.

extensive emergence of land in the interior at the close of the Ordovician period. Throughout much of the western part of the continent also, the land may have emerged at about this time, for the Silurian system is wanting, or has not been recognized, in many regions where the Ordovician is present.

Folding movements were less wide-spread. The most considerable was in the Taconic Mountains, where both the Cambrian and Ordovician systems were thick. Both were folded and lifted above the sea beneath which they had accumulated. The eroded remnants of the folds often show a complicated structure. The date of the folding is known, because Silurian formations overlies the Upper Ordovician unconformably about the borders of this mountain region. It is not to be inferred that all the mountain-making movements which have affected western New England occurred at this time. There had been folding earlier, in pre-Cambrian times, and there were later movements, as will be noted.

Between folding and the more gentle movements already noted there are all gradations. The "Cincinnati arch" is an example. This arch is a very low anticline with a general north-south course, extending through Cincinnati. The beginning of this arch may have been as early as mid-Ordovician.¹ Another similar arch² may have come into existence at about the same time in Arkansas and Oklahoma, corresponding in position with the mountain system commonly known as the Ouachita Uplift, of which it was perhaps the beginning. The strata of this region were notably folded at a much later time. In some other places, as for example in New Brunswick and Nova Scotia, there is unconformity between the Ordovician strata and those which overlies them, indicating an emergence after the deposition of the Ordovician formations.

The crustal movements referred to above have been mentioned as occurring at the close of the Ordovician. It would perhaps be more accurate to say that their beginning marks the beginning of

¹ Hayes and Ulrich, Columbia (Tenn.) folio, U. S. Geol. Surv.; also Foerste, Geol. Soc. of Am., Vol. XI, p. 604, and Vol. XIII, p. 531; Science, New Ser., Vol. X, p. 488, and 24th Ann. Rept., Dept. of Geol. and Nat. Hist., Resources of Indiana, 1899.

² Branner, Am. Jour. Sci., Vol. IV, 1897, p. 357. This very suggestive article has bearings on many questions besides the Ouachita Uplift.

the transition from the Ordovician period to the Silurian. The duration of the interval of transition was probably long.

Economic Products

In Ohio and eastern Indiana the Trenton formation yields much gas and oil.¹ Both these substances are believed to be products of the decay or distillation of organic matter which was included in the sediments at the time of their deposition. The oil is most abundant under low anticlines, where it occurs in the pores and openings of the rock, somewhat as ground-water does.

The Galena and Trenton formations in Wisconsin² and in the adjacent parts of Iowa and Illinois contain ores of lead and zinc, mainly in the form of sulphides and carbonates. Lead ores are also found in the Ordovician (or Cambro-Ordovician) formations of southeastern Missouri,³ and lead and zinc ores in the south-central part of the same state. In all these regions the ores occur (1) in cavities formed by solution, (2) as replacements of limestone, or (3) in crevices. In these positions, the ore was concentrated by ground-water. The metallic substances were doubtless derived from the limestone itself, which, at the time of its deposition, is thought to have contained trifling amounts of lead and zinc, derived from sea-water by organic deposition.

The Ordovician limestones of central Tennessee⁴ locally yield calcium phosphate, valuable as a fertilizer. The workable deposits have resulted from the leaching of phosphatic limestone, leaving the less soluble phosphate concentrated at the surface (Fig. 383). The Manganese ore of Arkansas had a similar origin. The metamorphic Ordovician limestones of New England and some parts of the Appalachian Mountains have been extensively used for marble.

Foreign Ordovician

The Ordovician formations appear at the surface in various

¹ Orton, 8th Ann. Rept., U. S. Geol. Surv.; Phinney, 11th Ann. Rept.; also the reports of the State Geol. Surv. of Ohio and Indiana.

² Chamberlin, Geol. of Wis., Vol. IV, 1879, pp. 365-568; Calvin and Bain, Iowa Geol. Surv., Vol. VI, and Grant, Bull. XIV, Wis. Geol. Surv., 1906.

³ Winslow, Missouri Geol. Surv., Vols. VI and VII.

⁴ Hayes, Columbia (Tenn.) folio, U. S. Geol. Surv.

parts of Europe, and they exist concealed by younger formations over considerable areas where they are not seen. Fig. 384 represents the general geographic relations of land and water in Europe during this period. The submerged area represents in a general way the area where the Ordovician formations are present.

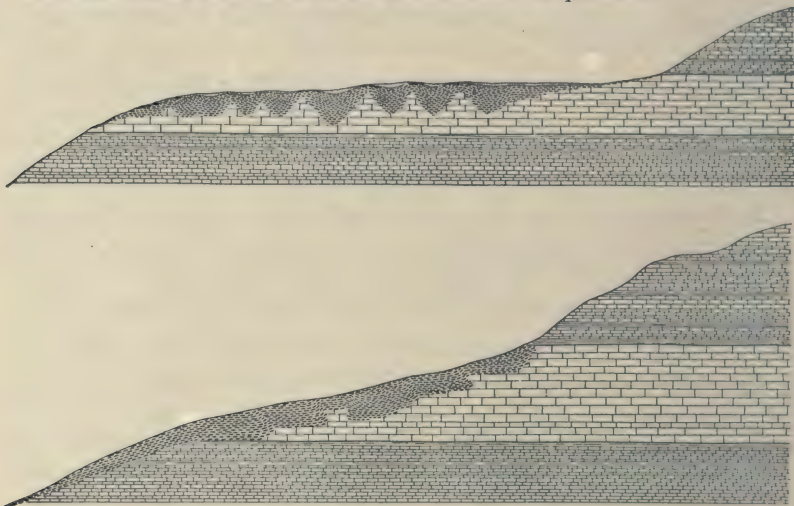


Fig. 383.—Shows modes of occurrence of the phosphates (the shaded surface parts of the limestone) in central Tennessee. (Hayes and Ulrich, *Columbia (Tenn.) folio*, U. S. Geol. Surv.)

The formations of the European Ordovician are largely fragmental, being made up of shales, sandstones, graywackes, etc., with which there is associated relatively little limestone. In this respect the Ordovician of Europe is in contrast with that of North America.

The system is represented in the British Isles by great thicknesses of strata (something like 24,000 feet maximum).¹ Locally (Wales), nearly half the system is composed of igneous rock, consisting of sheets of lava and beds of fragmental igneous rocks of various sorts. In the north of England, the successive beds of igneous rock, partly lava-flows and partly tuffs, not interstratified with aqueous sediments except near the base and summit, suggest that the eruptions took place, in part at least, on land. In Wales,

¹ This measurement is doubtless subject to the strictures set forth on p. 461.

on the other hand, the igneous rocks are interstratified with sedimentaries, and are therefore thought to have been ejected beneath water.¹ This is one of the most extensive, as well as one of the most ancient, volcanic tracts of Europe. From north England and Wales the system thins in all directions. In Scandinavia and Russia it has but a fraction of the thickness which it possesses in

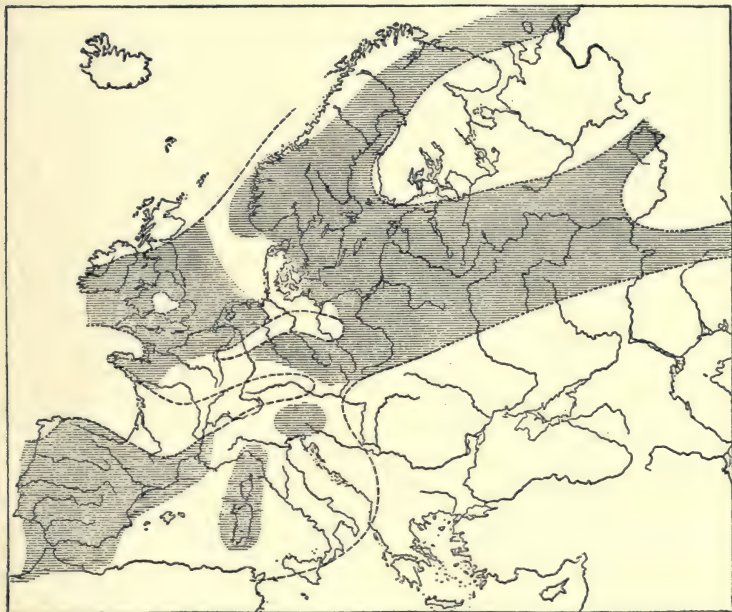


Fig. 384.—Diagram showing the relations of land and water in western Europe in the Ordovician period. The shaded parts represent areas of marine sedimentation. (After DeLapparent.)

Britain. In southern Europe the system does not attain great thickness, and limestone is more abundant than in the north. The strata are exposed about various mountains where local disturbances have upturned them, and where erosion has cut off the beds which once overlay them.

In Bohemia, though the system does not appear at the surface

¹ Geikie, *op. cit.*, pp. 946 and 949.

over a great area, it has been made classic by Barrande,¹ who has studied its abundant fossils in great detail. The faunas of few areas in any part of the earth have been studied with equal care, or with richer results.

The Ordovician of Europe is generally conformable on the Cambrian, but over considerable areas it is unconformable beneath the Silurian. In the British Isles, the stratigraphic relations of these systems show that the Ordovician strata were elevated, folded, crumpled, and so metamorphosed as to greatly change their character at the close of the Ordovician period. In the highlands of northwestern Scotland, the dynamic action seems to have been exceptionably severe. The strata here were not only folded, but the folds were overturned, and a series of nearly horizontal faults or thrust planes developed. Locally the thrust was as much as ten miles,² and had for a result, the burial of the Ordovician strata, sometimes without metamorphism, by the Cambrian and even the Archean rocks. Over the greater part of the European continent, on the other hand, orogenic disturbances do not appear to have taken place at the close of the Ordovician. In Europe, as in America, the great disturbances took place where thick bodies of sediment had been accumulated (or else the beds were greatly thickened by the disturbances).

In other continents the Ordovician strata have not always been separated from the overlying Silurian, but they are known both in Australia and China.

Duration and Climate

The duration of the Ordovician is perhaps no better known than that of the Cambrian, but the period was probably somewhat shorter than its predecessor.

Neither in Europe nor in America is there decisive evidence that climatic zones were distinctly marked. All that is known of the life of this area would seem to indicate that the climate was much more uniform than now throughout the areas where the strata of the period are known. The fact that the Ordovician rocks have

¹ *Système Silurienne de la Bohême.*

² *Quart. Jour. Geol. Soc., 1884 and 1888.*

been identified in the far north (in North Devon, the west coast of King William's Land, Boothia, etc.) by fossils akin to those of low latitudes, indicates that the climatic conditions of North America and Europe must have been less diversified than now. This apparent lack of diversity of temperature through wide ranges of latitude is one of the unexplained problems of geology. Its solution is possibly to be found in a much higher average temperature of the ocean, due to a deep circulation the reverse of that which exists now.¹ If the body of the ocean-water was relatively warm (instead of cold as now), it would have done much to counteract the effect of slight insolation during the cooler part of the year.²

LIFE

Just as no great physical change took place in the passage from the Cambrian to the Ordovician period, so there was no pronounced break in the succession of life. The time from the beginning of the Cambrian to the close of the Ordovician appears to have been one long eon of progressive development and expansion of life, and its division into two nominal periods is artificial rather than natural.

The fossil record of the Ordovician is fuller than that of the Cambrian. This is due partly to an increase in fossilizable forms, partly to an increase in numbers of individuals, and partly to better conditions of preservation.

The general aspect of life was cosmopolitan, though it was not the same everywhere. It varied with the physical evolution of the continent, and largely as the result of it. The variations assumed three general phases: (1) adaptation to the immediate physical environment, particularly the nature and depth of the sea-bottom (*edaphic adaptation*); (2) modification by auto-evolution within restricted areas isolated by barriers (*provincial evolution*), and (3) modification toward a universal type through intermigration (*cosmopolitan development*).

¹ Chamberlin, Proc. Am. Phil. Soc., Vol. XLV, 1906, pp. 1-11.

² Chamberlin and Salisbury, Earth History, Vol. III, pp. 437-445

(1) **Edaphic modification.** Rocky, sandy, muddy, and calcareous bottoms had their appropriate life, as did also tracts of shallow and deep water, and areas dominated by other special conditions. The assemblages adapted to these special conditions were not altogether unlike, for not a few forms, particularly free-swimming species, were indifferent to these conditions.

(2) **Provincial modifications.** Although the sea covered a large part of the continent, affording facilities for the migration and mingling of faunas, there was still evidence of some separation into zoölogical provinces. This was probably due partly (1) to barriers interposed by gentle warpings of the sea-bottom producing emergent tracts and tracts of excessive depth, and partly (2) to barriers constructed by the sea itself, in the form of shoals, bars, and spits. Provinces may have been defined also by (3) ocean-currents with their attendant differences in temperature, and they may have been due (4) to variations in the salinity of the waters. Provinces due to surface warpings seem to have been most marked in the Appalachian tract.¹

(3) **Cosmopolitan development.** Notwithstanding the local and provincial modifications just noted, the progress of the Ordovician life on the American continent seems to have been, on the whole, in the direction of cosmopolitanism. This was due, primarily, to the wide development of the epicontinental seas, which gave a broad field for the evolution of marine life, and permitted free migration. A cosmopolitan tendency is particularly marked in the great interior of the continent. These statements apply chiefly to the shallow-water faunas. The deep-sea beds of the period are inaccessible.

The Ordovician system contains an exceptionally large number of fossils of free-floating graptolites (Fig. 394).² Their remains are mingled with the fossils of the shallow-water life, showing that pelagic life swam freely over the epicontinental seas. The Ordovician graptolites are nearly identical in Europe, North America,

¹ Paleozoic Seas and Barriers; E. O. Ulrich and Charles Schuchert, Rept. N. Y. State Paleontologist, 1901, pp. 633-658.

² It is not universally agreed that all graptolites were floating forms at all stages, but there seems to be little doubt that they usually were in their young stages at least.

and Australia, so that the range of the graptolite species was ocean-wide. The history of individual species was not long, geologically speaking, and hence the succession of species is well suited for marking the progress of events in all parts of the ocean. During the lifetime of the graptolites (limited to the late Cambrian, Ordovician and Silurian), a score of successive zones, each characterized

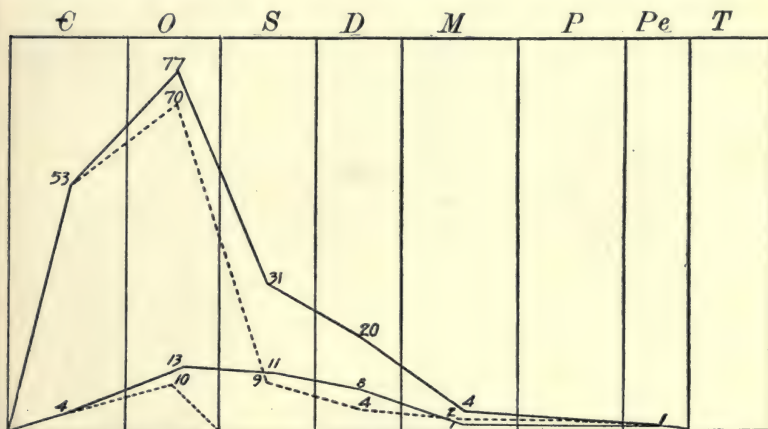


Fig. 385.—The two upper curves represent the history of the trilobites according to genera, the full line indicating the total number of genera, and the dotted line the number of new genera introduced. The two lower curves present the same data for the families of the trilobites, the full line representing the total number of families present, and the dotted line the number of new families introduced. The data for the families is taken from Beecher in the Zittel-Eastman text-book of Paleontology, Vol. I. The data for the genera is somewhat incomplete, but is as full as can be made from Zittel's "Handbuch der Paläontologie."

by particular species, have been identified. One of these zones falls in the Cambrian, eight in the Ordovician, and eleven in the Silurian. If these be taken as chronological bench-marks, the successive horizons of the different continents may be correlated accurately, and the progress of life in the various quarters of the globe referred to a common standard.

The Record of Marine Life

The known fauna of the Ordovician was made up almost wholly of marine invertebrates, among which trilobites and brachiopods

held the leading places. The brachiopods were most numerous, the trilobites highest in organization, and the cephalopods most powerful. But the foreshadowings of a new dynasty were at hand, for the remains of fish have been found in the strata of this system.

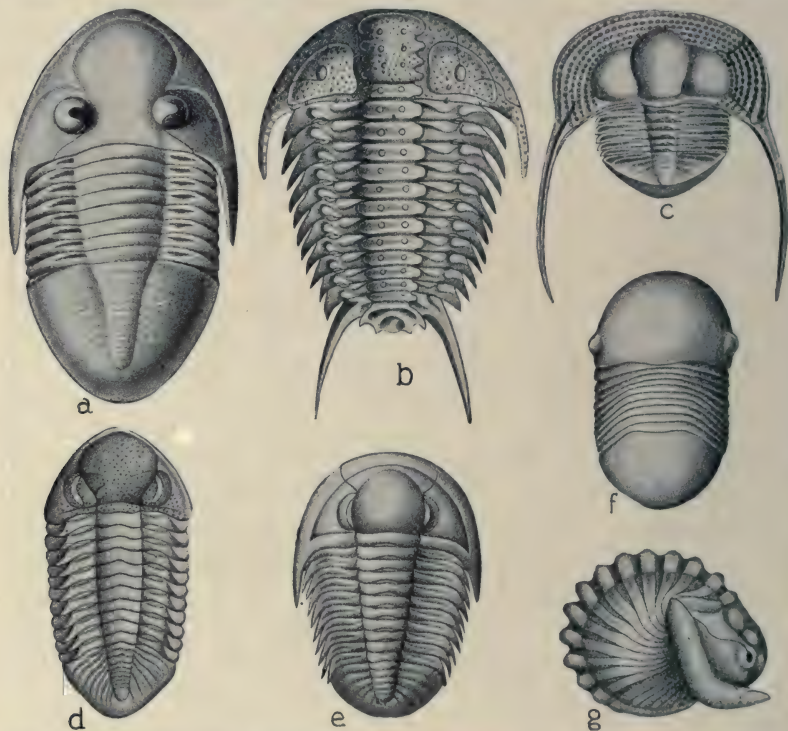


Fig. 386.—Ordovician Trilobites: a, *Isotelus maximus* Locke; b, *Ceraurus pleurexanthemus* Green; c, *Trinucleus ornatus* Sternberg; d, *Pterygomotopus callicephalus* (Hall); e, *Proetus parviusculus* Hall; f, *Bumastus trentonensis* (Emmons); g, *Calymene callicephala* Green.

Trilobites and other crustaceans. The rise and fall of the trilobites is shown in the curve of Fig. 385. Their climax in the Ordovician appears to have been reached by a rapid ascent, which was followed by a more gradual decline. More than half of all known genera of trilobites are represented in the Ordovician system, but only a few lived over from the Cambrian. In the next period the

numbers fell off a full half, and this decline continued until the tribe became extinct. The general aspect of the trilobites at the high tide of their career is fairly illustrated in Fig. 386. Their eyes were, as a rule, more prominent and better developed than those of the Cambrian species. There was little or no increase in average size. Some individuals reached a length of 18 inches and ranked

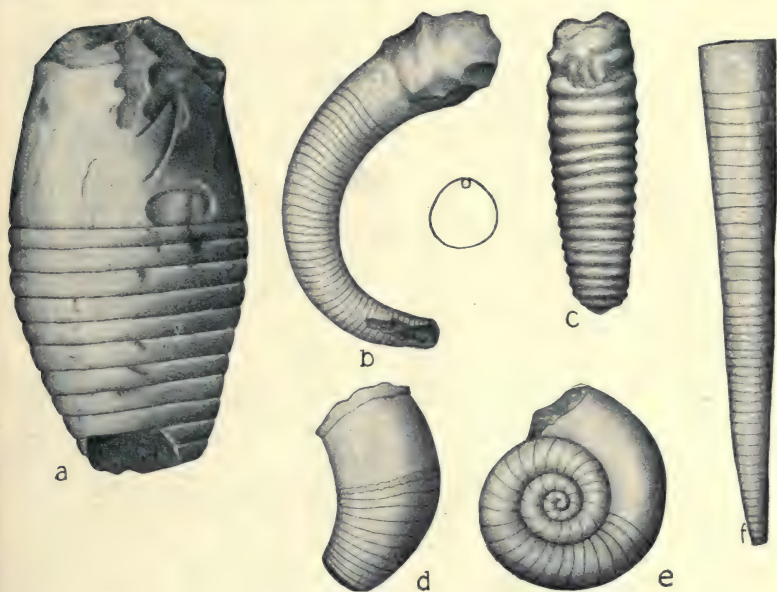


Fig. 387.—Ordovician Cephalopods: *a*, *Poterioceras apertum* Whiteaves; *b*, *Cyrtoceras neleus* Hall; *c*, *Orthoceras bilineatum* Hall; *d*, *Oncoceras pandion* Hall; *e*, *Trocholites ammonius* Conrad; *f*, *Orthoceras sociale* Hall.

among the giants of the group, but this size was equaled and even surpassed by some of their Cambrian forebears.

Besides the trilobites, the crustaceans were represented by a few inferior forms, such as ostracodes (Fig. 372) and cerripeds.

The Cephalopods. The largest, most powerful, and perhaps most predaceous of the known forms of Ordovician life were the cephalopods, which seem to have developed into prominence with extraordinary suddenness. Unless the fishes, of which little is

known, contested their supremacy, they were doubtless the undisputed masters of the sea. Their relics first appear at the time of the transition from the Cambrian to the Ordovician, but they were then so far advanced and so widely differentiated from allied forms as to render it probable that they had already lived a long time. Their general aspect is seen in Fig. 387. The dominant form, as



Fig. 388.— Ordovician Gastropods: *a*, *Subulites regularis* U. and S.; *b*, *Mac-lurea logani* Salter; *c*, *Lophospira helicteres* (Salter); *d*, *Cyclonema bilix* (Conrad); *e*, *Schizolopha textilis* Ulrich; *f*, *Conularia trentonensis* Hall; *g*, *Hormotoma gracilis* (Hall); *h*, *Eccyliomphalus triangulus* Whitfield; *i*, *Helicotoma planulata* Salter; *j*, *Cyrtolites ornatus* Conrad; *k*, *Raphis-tomina lapicida* (Salter); *l*, *Protowartha cancellata* (Hall); *m*, *Bellerophon clausus* Ulrich; *n* and *o*, *Archinacella cingulata* Ulrich.

well as the most primitive one, was the *Orthoceras* (Fig. 387, *c* and *f*), whose shell consisted of a long, straight, gently tapering cone divided into chambers by plane septa, and connected by a central tube (the *siphuncle*). Even in the Ordovician period there was a wide departure from the ideal simplicity of this genus. There were curved forms and coiled forms, some of which resemble the *Nautilus* of to-day (Fig. 387, *e*). Straight forms predominated, however,

and the sutures (junctions of the septa with the outer shell) were simple. In later periods the sutures vary widely, and marked, in a very tangible way, the progress of the class. The size attained by the Ordovician cephalopods was probably never surpassed by representatives of the class. Some of the shells were 12 or 15 feet in length, and a foot (maximum) in diameter. From this great size they ranged down to or below the size of a pipe-stem.

Other Molluscs. The *gastropods* were well represented in the early Ordovician fauna by diverse forms (Fig. 388). Few types

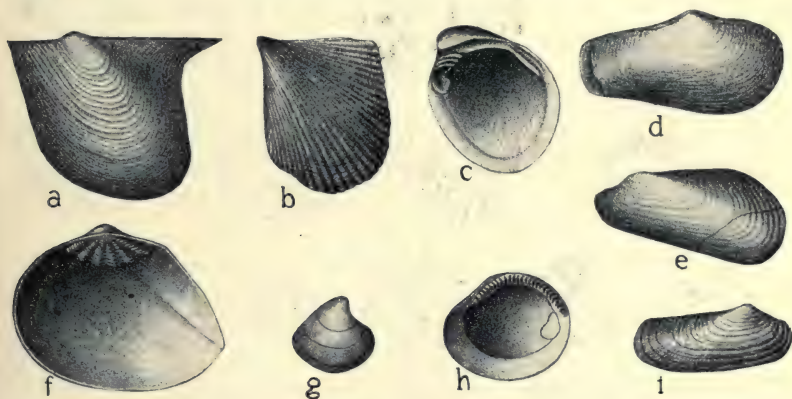


Fig. 389.—Ordovician Pelecypods: a, *Pterinea demissa* (Conrad); b, *Bysso-nychia radiata* (Hall); c, *Vanuxemia dixonensis* M. and W., interior of right valve, showing the hinge and muscular impressions; d and e, *Ctenodonta nasuta* (Hall); f, *Lyrodesma cincinnatiensis* Hall, interior of right valve, showing a primitive type of hinge; g, *Ctenodonta recurva* Ulrich; h, *Ctenodonta pectunculoides* Hall; i, *Rhytimya radiata* Ulrich, exterior of right valve.

of early Paleozoic life so closely resembled their modern relations. The *pelecypods* were subordinate to the *gastropods* both in numbers and range. Representative forms are shown in Fig. 389. Like their modern relations, the Ordovician pelecypods seem to have been fond of muddy and sandy bottoms, for they are rather rare in the limestone beds of the early and middle Ordovician. They increase in abundance as the deposits grade into the shales of the later Ordovician.

The Brachipods. The lower, inarticulate forms of brachipods which predominated in the Cambrian, continued through the Ordo-

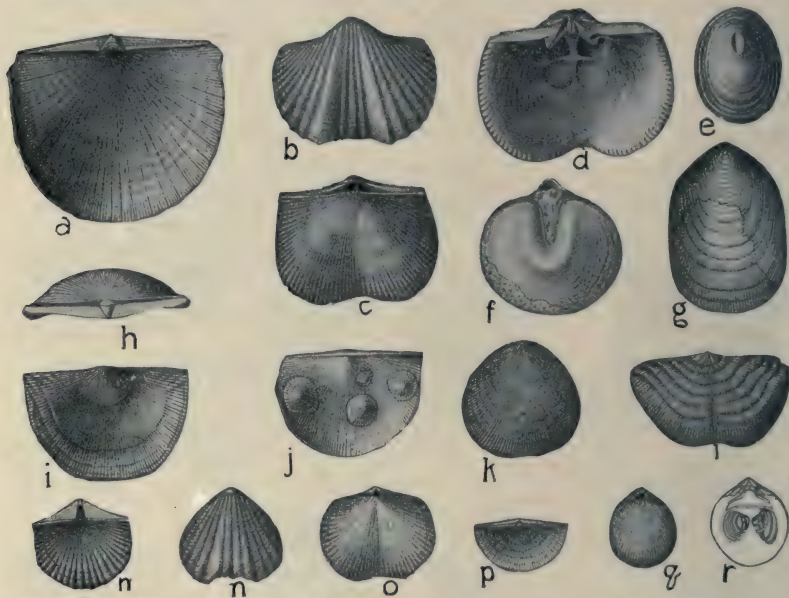


Fig. 390.—Ordovician Brachipods: *a*, *Rafinesquina alternata* (Emmons); *b*, *Platystrophia lynx* (Eich.); *c*, *Hebertella sinuata* (Hall); *d*, *H. sinuata* (Hall), interior view of the brachial valve, showing muscular impressions and hinge; *e*, *Schizotreta ovalis* H. and C., a pedicle valve; *f*, *Trematis millepunctata* Hall, pedicle view of a complete shell, showing the unmodified notch-like pedicle opening; *g*, *Lingula rectilateralis* Emmons; *h-i*, *Strophomena subtenta* Conrad, posterior view of a complete shell, showing the hinge-line, etc., and the exterior of the concave pedicle valve (*i*); *j*, *Crania laelia* Hall, brachial views of four individuals attached to another shell; *k*, *Schizocrania filosa* (Hall), a brachial valve; *l*, *Leptæna rhomboidalis* Wilck, the pedicle valve; *m*, *Orthis tricenaria* Conrad, exterior of the brachial valve and the cardinal area of the pedicle valve; *n*, *Orthis tricenaria* Conrad, exterior of the brachial valve and the cardinal area of the pedicle valve; *o*, *Rhynchotrema capax* Conrad; *o*, *Dalmanella testudinaria* (Dal.), brachial view; *p*, *Plectambonites sericeus* (Sow.), brachial view; *q*, *Catazyga headi* (Bill.), brachial view; *r*, *Zygospira recurvirostris* (Hall), interior of a brachial valve, showing the spiral brachidium in position.

vician (and to the present time), but the higher, articulate forms greatly outnumbered them. The expansion of the articulate types was attended by a progressive evolution of the mode of articulation.

In some the length of the hinge was increased, apparently affording a better means of resisting the attempts of their enemies to reach them by sliding or rotating the valves past one another (*i* and *p*, Fig. 390), while in others the margins of the valves were notched so that the valves interlocked *n*. The latter device was

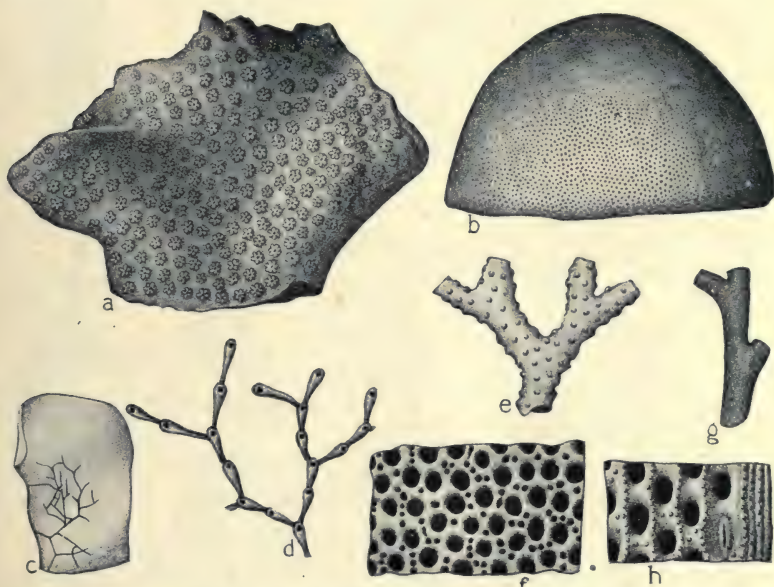


Fig. 391.—Ordovician Bryozoans: *a*, *Constellaria polystomella* Whitfield; *b*, *Crepipora hemispherica* Ulrich; *c-d*, *Stromatopora delicatula* (James); *d* is an enlarged portion of *c*. *e-f*, *Callopora pulchella* Ulrich, *f* being an enlarged portion of *e*; *g-h*, *Rhinidictya mutabilis* Ulrich, *h* being an enlarged portion of *g*.

usually best developed in the shells of narrow and weak hinge-line, where it was most needed. In addition to these devices for preventing the opening of the shell, there was generally a thickening of the shells, and in many cases a ribbing of the exterior, giving strength without needless weight. All these devices seem to imply that the enemies of the brachiopods had increased in effectiveness, but the abundance of the brachiopods implies that their enemies did not gain the mastery. A comparison of the figures of Ordovician and

Cambrian brachiopods (Figs. 390 and 373) will illustrate, in some degree, their changes.

The Bryozoans. The bryozoans (Fig. 391), kin to the brachiopods (p. 945) were very unlike them in external form, in habits,

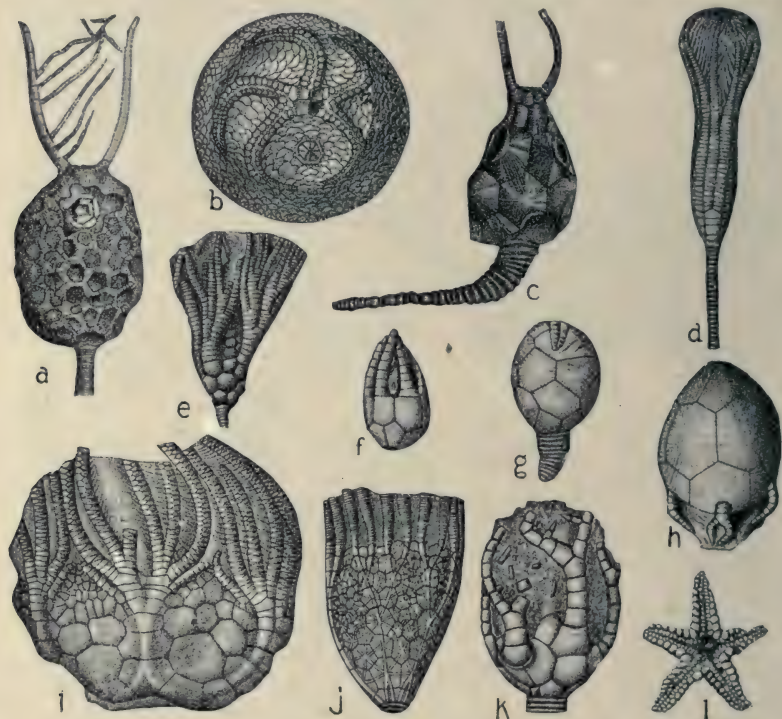


Fig. 392.—Ordovician Echinoderms: *a*, *Comarocystis punctatus* Billings; *b*, *Lepidodiscus cincinnatiensis* (Roemer); *c*, *Pleurocystis filitextus* Billings; *d*, *Ectenocrinus grandis* (Hall); *e*, *Dendrocrinus polydactylus* (Shumard); *f*, *Hybocrinus tumidus* Billings; *g*, *Lepadocystis moorei* (Meek); *h*, *Carabocrinus vancortlandti* Billings; *i*, *Archæocrinus desideratus* Billings; *j*, *Glyptocrinus decadactylus* Hall; *k*, *Anomalocrinus incurvus* M. and W.; *l*, *Paleaster simplex* Miller. *a*, *b* and *c* are cystoids, *d*-*k* are crinoids, *l* is a star-fish. Cystoids and crinoids were the most numerous echinoderms of the Ordovician.

and in their hard secretions. The bryozoans lived in colonies, connected by a common mantle which secreted calcareous material to form the framework of the colony. These secretions so closely re-

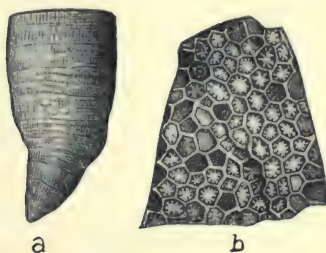


Fig. 393.—Ordovician Corals: a, *Streptelasma corniculum* Hall; b, *Columnaria alveolata* Goldf. Both simple and compound corals were present in the Ordovician faunas, but they rarely formed great reefs as in later periods.

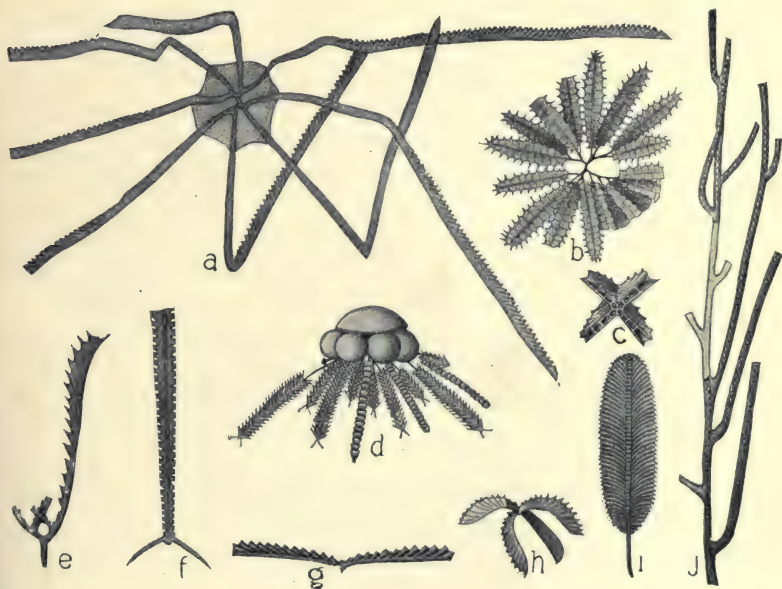


Fig. 394.—Ordovician Graptolites: a, *Dichograptus octobrachiatus* (Hall); b, *Reteograptus eucharis* Hall; c, *Phyllograptus ilicifolius* Hall; d, *Diplograptus pristis* (Hall) (restored by Ruedemann); e, *Tetragraptus fruticosus* (Hall); f, *Climacograptus bicornis* (Hall); g, *Didymograptus nitidus* (Hall); h, *Tetragraptus bigsbyi* (Hall); i, *Phyllograptus typus* Hall; j, *Holograptus richardsoni* (Hall).

semble coral that they have often been mistaken for it. The bryozoans became abundant in the middle and later portions of the period, when their secretions contributed much to the limestone.

The Echinoderms. One division of the echinoderms, the *cystoids*, reached its climax before the close of the Ordovician period; another, the *crinoids*, became prominent, and others (asteroids, ophiurians, and echinoids, p. 945) had made their appearance. The cystoids, (*a*, *b*, and *c*, Fig. 392) with their irregular forms, were the most primitive, and gave place in time to the more symmetrical crinoids (Fig. 392, *d* to *k*), which may be likened to star-fishes turned face uppermost and fixed to the sea-bottom by a calcareous stem attached to the center of the back. The crinoids so closely resembled a flower in form, that the familiar name "sea-lily" is not inappropriate. The crinoids were excellent subjects for fossilization, save that, after the tissues decayed, the constituent hard portions fell apart easily so that perfect specimens are rare. Some limestone is made up largely of crinoidal fragments.

The structure of the cystoids (Fig. 392, *a* to *c*) was similar to that of the crinoids, but the body was unsymmetrical both in form and in the arrangement of the plates. Little can be said of their evolution, for their forms are so heterogeneous and their functions so little known that it is not clear what constituted progress. The other echinoderms attained their principal development later.

The cœlenterates. *Corals* are few in the lower part of the system, and though more abundant in higher beds, are nowhere a leading element in the fauna. Most of them belonged to the simpler horn-shaped type (Fig. 393, *a*), but compound and colonial corals were present. The most important development of the cœlenterates was the rise of the *graptolites* (Fig. 394), whose important function in correlation has been referred to.

Other forms. Sponges were present and sometimes attained notable size (Fig. 395). The record of *annelids* is more meager than in the Cambrian, perhaps because the calcareous sea-bottom of the Ordovician was less congenial to them than the Cambrian sands. They are represented by burrows and by teeth (Fig. 396). Protozoans were probably present, but their minute and fragile shells can be recognized only with some uncertainty.

Fishes. Fragmentary fossils of fishes constitute the most striking innovation in the record of the marine life of the Ordovician period. These have been found in a few localities only, notably near Canyon City, Colo., and in the Bighorn Mountains of Wyoming.

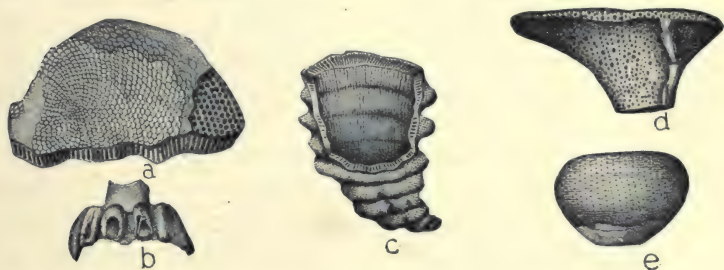


Fig. 395.—Ordovician Sponges: a, *Receptaculites occidentalis* Salter; b, *Brachiospongia digitata* Beecher; c, *Archæocyathus minganensis* Billings; d, *Strotospongia maculosa* U. and E.; e, *Ischadites*, species undetermined. The *Receptaculites* and *Ischadites* have sometimes been regarded as giant foraminifers.

Implied life. If we inquire what forms other than those fossilized are necessary to round out a rational assemblage of life, a briefer answer may be given than in the case of the Cambrian life,

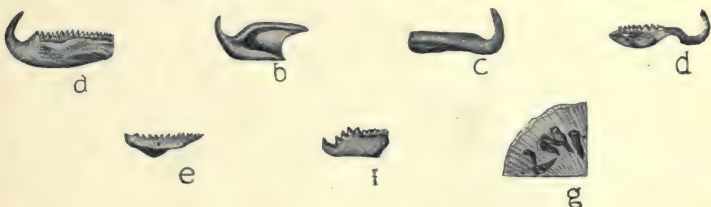


Fig. 396.—Ordovician Annelids: a, *Arabellites cornutus* Hinde; b, *Glycerites sulcatus* Hinde; c, *Eunícites gracilis* Hinde; d, *Arabellites ovalis* Hinde; e, *Eunícites varians* (Grinnell); f, *Oeononites rostratus* Hinde; g, *Ortonia minor*. Nicholson. a-e are highly magnified illustrations of the jaws of annelids.

for the Ordovician fauna was a nearer approach to a theoretically complete assemblage. As in the Cambrian, a vast supply of unrecorded vegetation must be postulated as a food-supply. To provide for organisms that preyed upon one another in succession, from plants up to the master forms of the predaceous animals, there

were doubtless many species not now known. The defensive investitures of the lower forms, not fully accounted for by the known Cambrian species, are now much more nearly explained by the prevalence of cephalopods and the presence of fishes. The armors of these dominant forms may have been defensive against their own kind. The fact that vegetal and animal tissues are not represented among fossils, save in exceptional cases, probably signified that the bacteria concerned in the decomposition of organic matter were abundant.

Ecological, social, and mental development. It seems clear that the adaptation of the various forms of life to one another and to their physical environment had reached a higher stage of adjustment than in the Cambrian, an adjustment not greatly inferior to that which now prevails among the corresponding orders. It is not improbable that the mental development also approached somewhat nearly that now possessed by corresponding types. Higher types within the same orders have been developed since in many cases, and probably higher mental functions; but some of the Ordovician forms have since suffered degeneration. The Ordovician ancestors of the barnacle, for example, a free-moving, active form, was doubtless superior to his sessile descendant of ill-repute. The sum total of ecological adaptation and of social and mental development, on the average, seems to have advanced with each era.

The Record of Land Life

Plants. There are strong theoretical reasons for believing that land plants abounded, but only a few relics doubtfully interpreted as land plants have been found, and they reveal but little.

Insects. The oldest relic of insect life now known is a rather obscure wing found in the graptolite shales of the Upper Ordovician of Sweden. It is referred to the order of *Hemiptera* (bugs). Not enough is preserved to show fully the nature of the insect, but the existence of any flying insect of this sort implies the presence of vegetation, and of atmospheric conditions suited to active, air-breathing organisms.

Succession of faunas. There was a succession of Ordovician faunas, somewhat unlike one another, just as there was a succession

of Cambrian faunas. These may be distinguished roughly as the Lower, the Middle, and the Upper Ordovician faunas. In some places, the late Cambrian faunas and the early Ordovician faunas merge into one another without sharp definition. In general, the Mid-Ordovician fauna was more prolific than that which preceded, if we may judge from the fossils. The Mid-Ordovician fauna, too, was distinctly cosmopolitan. The Upper Ordovician fauna was similar to its predecessor, from which it descended, but the prevailing muddiness of the bottom of the late Ordovician seas seems to have had some influence on the life, and clear-water forms were less dominant.

The successive sub-faunas of the period were much the same in other continents as in America. Most genera were the same, but the species were, as a rule, different, though they often bore a close resemblance to the American species. In northwestern Europe, with which the means of migratory communication seems to have been freest, not a few common American species flourished. In Asia, so far as present limited information goes, the species were nearly all different, the wide-ranging graptolites excepted. The stages of progress in the shallow-water faunas of the Old and New World, are to be regarded as parallel rather than identical. The evolution in Europe, where alone details have been well worked out, was usually on narrower lines than that of the American interior, for the obvious reason that the epicontinental seas were more limited and more interrupted by barriers.

Map Work. The folios which serve for the study of the Cambrian system (p. 506) are serviceable also for the Ordovician. In the folios, however, the Ordovician and Silurian systems are put together on the *maps*, under the name *Silurian*; but the *texts* of the later folios distinguish between the two.

CHAPTER XVIII

THE SILURIAN (UPPER SILURIAN) PERIOD

FORMATIONS AND PHYSICAL HISTORY

The physical changes which brought the Ordovician period to a close marked also the inauguration of the Silurian. These changes included (1) movements which affected small areas intensely, and (2) movements which affected broad areas slightly. From the standpoint of continental history, the latter were the more important. These changes were doubtless accomplished slowly, and after they had taken place, the area of land in North America was greater than at any time since the early Cambrian. The increase in land meant lengthened streams, and presumably increased erosion.

Could the distribution of land and water at the beginning of the Silurian be defined accurately, it would define also the areas where the earliest marine sedimentation of the period took place, and, in a general way, the areas where sedimentation was rapid and where slow, for then, as always, the rate of sedimentation must have stood in more or less definite relation to the shore-lines. It is safe to assume that at the opening of the Silurian period beds of clastic sediments were accumulating about the immediate borders of the lands, and as far out as waves and currents were able to transport abundant detritus, and that elsewhere sediments of organic origin were relatively more important. Though sedimentation was interrupted in the regions which emerged from the sea during the transition from the Ordovician period to the Silurian, such interruption was not universal, and the Silurian strata are locally conformable on the Ordovician in the continent, and generally, it is to be presumed, in the ocean basins.

Like the preceding system, the Silurian may be divided into three principal series, as follows:¹

Silurian	Cayugan (Upper Silurian)	- Manlius limestone - Rondout waterlime - Cobleskill limestone - Salina beds
	Niagaran (Middle Silurian)	- Guelph dolomite - Lockport limestone - Rochester shale - Clinton beds
	Oswegan (Lower Silurian)	- Medina sandstone - Oneida conglomerate (and perhaps the Richmond beds)

Each of these series is subdivided into several formations, but the subdivisions of one place do not fit another. A brief sketch of the nature and distribution of these principal subdivisions of the system affords an outline of the history of the continent during the period.

Silurian of the East

The Oswegan series. The principal subdivisions of this series in the east are the Oneida and the Medina. Both appear at the surface south of Lake Ontario, and perhaps in the western part of the Appalachians farther south.² The Oneida consists of conglomerates and sandstone, and the Medina of sandstone and shale. The sediments of these formations appear to have been deposited in a shallow interior sea, as shown by their fossils, and by the cross-bedding, the ripple-marks, etc., which affect its layers. The Medina formation extends farther west than the Oneida, reaching eastern Ohio and Ontario. Its distribution, as compared with that of the Oneida, points to a subsidence of the eastern interior during the early part of the Silurian period. Both formations are probably continuous beneath younger strata over considerable areas south of Lake Ontario and the Mohawk valley, and west of the Appalachians.³ Nothing is known of the sediments which were accumu-

¹ In this case, there is some infelicity in the use of the terms Lower Silurian, Middle Silurian, and Upper Silurian, for the subdivisions of the system, since Lower Silurian was long used as a synonym for Ordovician, and Upper Silurian for Silurian, as that term is here employed.

² Some of the formations formerly classed as Oneida in New York and New Jersey are now regarded as of Salina age (see p. 543).

³ Perhaps the Richmond beds, the Maquoketa shales, etc. See foot-notes, pp. 509 and 510.

lating along the eastern border of Appalachia at this time, nor of those about the other land areas.

The Niagaran series. The Clinton formation overlies the Medina conformably, but has a wider distribution. Westward, it extends to Lake Huron and Indiana, and perhaps to the Mississippi. If this is the case, it is represented by beds which have been classed with the Niagara limestone. The formation occurs in the Appalachians as far south as Alabama and Georgia. The fossils of the formation in the Appalachians are so unlike those of the interior, as to lead to the inference that the sites of sedimentation in the two areas were not freely connected. Beds of Clinton age have been recognized in Nova Scotia and at a few other places northeast of the United States. Marine sedimentation was probably continuous here through the Ordovician and Silurian periods.

The variations in the character of the Clinton beds in different localities are significant. In the Appalachian Mountains, the formation is largely of sandstone and shale. In western New York and farther west, much of it is limestone. The limestone does not mean that the water was necessarily deep, but rather that it was so nearly free from clastic sediments that the shells, etc., constituted the principal part of the deposit made. Shell-bearing life may be just as abundant where sand and mud are accumulating as elsewhere, but in this case the product is not limestone, but sandstone, shale, etc., containing shells. Bryozoan reefs, resembling coral reefs, occur in the formation in western New York.¹

One of the notable features of the formation is its content of *iron ore*, generally in the form of hematite (Fe_2O_3). The ore is often made up of small concretions which so resemble flaxseed in size and shape as to have suggested the name "flaxseed" ore. Locally it is known also as "fossil" ore from the abundance of fossils which it contains. The ore is known at many points between New York and Alabama, as far west as Wisconsin, and as far northeast as Nova Scotia. The ore is interstratified with other beds of the formation, and is usually believed to have been accumulated by chemical precipitation in lagoons or marshy flats.

Like the Oneida and Medina formations which preceded, the

¹ Sarle, *Am. Geol.*, Vol. XXVIII, p. 282.

Clinton beds have not been identified in the western half of the continent.

The Clinton formation was succeeded by the *Niagara formation* (subdivided in New York into Rochester shale, Lockport limestone, and Guelph dolomite, p. 537), which extends farther west than any of the preceding Silurian formations, showing that the progressive submergence of the earlier epochs still continued in the upper Mississippi basin. The falls of Niagara River are over the limestone of this series (Fig. 113). North of Missouri, the formation is not known to occur far west of the Mississippi, but it extends into Missouri, Arkansas, and perhaps even to the Arbuckle Mountains of Oklahoma. It is also found in the trans-Pecos region of Texas. It was in this epoch that the submergence of the upper Mississippi basin reached its maximum, so far as this period is concerned. The southern border of the interior sea is not known, but it appears to have been separated from the ocean in this direction, by a land barrier somewhere in the Gulf-State region (Fig. 397). The barrier was probably south of Tennessee, as Niagaran limestone occurs in the western part of that state.

A significant feature of the distribution of the Niagara formation is its great development in high latitudes. It occurs in patches in Manitoba, west of Hudson Bay, and at numerous points farther north, up to latitude 80°. The patches appear to be remnants of a once continuous formation, and since the fossils are much the same throughout, and very like those of northern Europe, it is inferred that there was water connection between the Mississippi basin and northern Europe by way of the Arctic islands, which permitted the intermigration of the shallow-water sea-life of the two regions.

East of the Appalachians and west of the Mississippi the distribution of Niagaran strata is not well known. They probably occur in New Hampshire and Maine, and in the Provinces between these states and the St. Lawrence. In Nova Scotia, the Niagaran series is represented by shale, affording another illustration of the fact that different sorts of rock may be accumulating in different regions at the same time. The exact equivalent of the Niagara formation has not been identified with certainty in the West.

West of New York the formation is mainly limestone. Perhaps

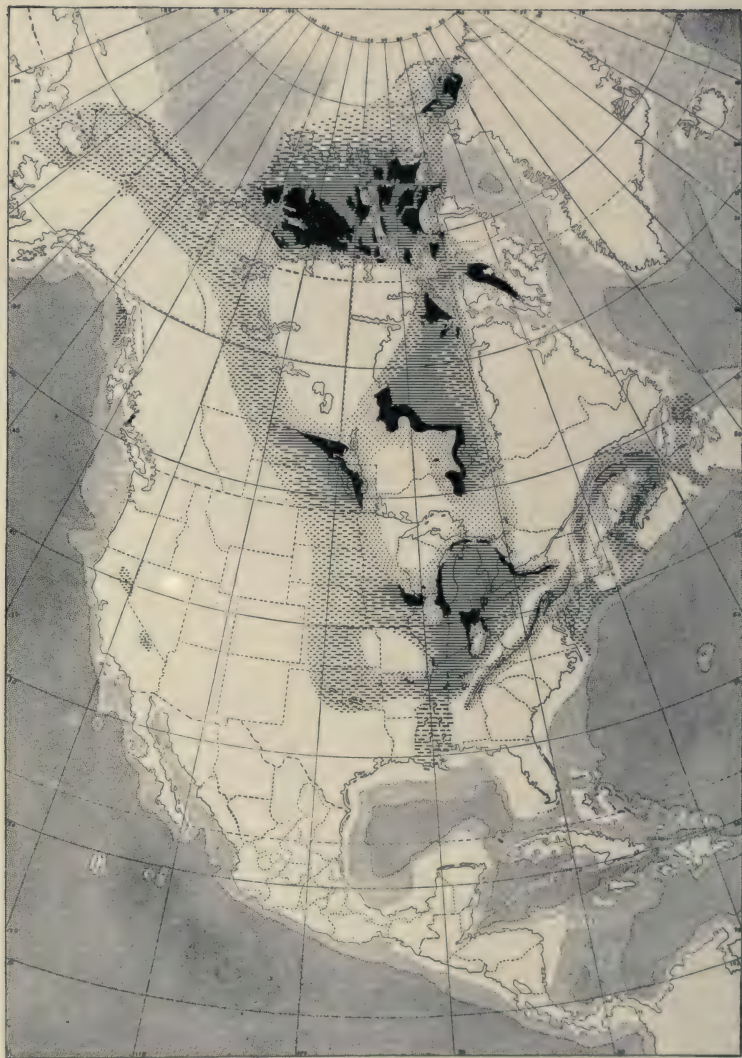


Fig. 397.— Map showing the outcrops of the Niagara formation, and at the same time the general relations of land and water during the Niagara epoch. The various sorts of shading on the map correspond with those on earlier maps (see p. 469).

no preceding formation of limestone except the Trenton is so widespread. It is the oldest formation in which well-developed *coral reefs* have been identified, though coral-secreting polyps had lived before (p. 532). The reefs are known in eastern Wisconsin, Indiana, and elsewhere.

These reefs and the deposits adjacent to them illustrate as clearly as anything among the ancient formations, the origin of several varieties of limestone. The reefs themselves are composed of the commingled relics of the life that grew upon them. Great masses of coral sometimes stand erect in the rock just as they grew, having escaped destruction during their burial in the growing reef. In other instances, the coral masses in the limestone are fragmentary, broken and worn by the waves. With the larger pieces of coral

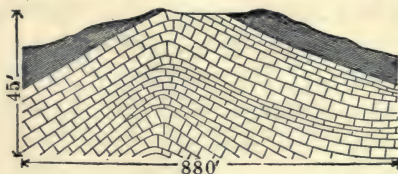


Fig. 398.—The Wabash dome in the Niagara limestone. (Kindle.)

there is coarse and fine detritus, the product of coral comminution. These combine to make up the mass of the reef-rock. Between and about the reefs a mixture of shell and coral fragments and calcareous sands accumulated, growing finer as distance from the parent reef increased and the slope of the bottom became more gentle, these materials grading finally into calcareous mud, which was spread widely over the sea-bottom about the reefs. This fine calcareous sediment ultimately gave rise to compact white limestone.

Thickness and structure. Unlike the preceding formations of the Silurian, the Niagara is not thicker in the east than elsewhere. In the east, indeed, where the formation is exposed, it has a thickness of but 100 to 300 feet, while in Wisconsin it attains a maximum of 800 feet (perhaps including some Clinton), all of which is limestone. While the Niagaran beds of the interior are in general nearly horizontal, they are frequently domed so as to give the beds a high angle of dip (Fig. 398). This is true, for example, at various points about the southern end of Lake Michigan.

The Cayugan (Salina) series. The Salina formation, which overlies the Niagaran in parts of New York, Pennsylvania, Ohio, Michigan, and Ontario, is much less widespread, and its limited distribution points to the emergence of a considerable area in the Mississippi basin at the close of the Niagaran epoch.

The Salina series embraces several varieties of rock, including conglomerate, sandstone, limestone, shale, and rock salt. With these formations, some gypsum, the usual accompaniment of salt beds, is associated. Shale is the most abundant, and seems to have originated after the fashion of shales in general, but the fewness of its fossils seems to point to deposition under conditions unfavorable for life.

The salt is widely distributed. It occurs at many points in New York within an area 9,000 to 10,000 square miles in extent. Single beds of it are locally 40 to 80 feet thick. Several beds sometimes occur one above another, interstratified with other sorts of rock, and their aggregate thickness sometimes reaches as much as 100 feet. Near Cleveland, four salt beds, 50 feet and less in thickness are interstratified with 500 feet of shales. In some places, therefore, the salt makes a very considerable fraction of the total thickness of the series.

The salt beds seem to imply the existence of great lagoons or inclosed seas, in which the Salina series was deposited. Had the climate of this region been as moist as now, these lagoons could not have been abnormally saline. Occasional incursions of the sea, bringing in new supplies of salt water, followed by periods when the lagoons were cut off from the sea, and when they suffered rapid evaporation, would seem to meet the conditions demanded for the formation of the salt. So also would a slight continuous connection with the sea, such that the inflow of sea-water into the basin did not balance the excess of evaporation over precipitation in the basin area. A bed of salt 40 feet thick implies the evaporation of some 3,000 feet of normal sea-water. Much of the salt of commerce which comes from New York is not derived immediately from the salt beds, but from the waters of salt wells.

The limestone of the Salina proper is largely contemporaneous with the shales and salt beds. It is thickest where they are thin,

and thin where they are thickest. It contains few fossils, and it is thought that it may be a chemical precipitate. Its relations to the shales and salt beds are such as to indicate that the areas of accumulation of the several sorts of rock material were shifted from time to time, as if by gentle changes of level of land or water.

Above the Salina proper of New York, there is a thin (150 feet maximum) series of limestones, the *Waterlime* (Cobleskill, Rondout, Manlius, etc.), generally regarded as a part of the Silurian system. The name Waterlime has reference to the fact that the limestone is the source of hydraulic cement, though it is by no means everywhere useful for this purpose, and many other limestone formations are similarly used. The Waterlime is more widespread than the Salina, extending westward through Ohio to Indiana and Wisconsin. Both its distribution and its character show that the eastern interior was more generally submerged than during the deposition of the salt-bearing series which preceded.

In the northern Appalachians there is a conglomerate formation (Shawangunk, N. Y., Green Pond Mountain, N. J.), formerly classed as Oneida, which is now regarded as contemporaneous with the Cayugan series. Until recently, this conglomerate was not known to contain fossils, but their discovery has shifted the classification of the formation from the early Oswegan to the later Cayugan series.¹ The materials of this conglomerate are mostly quartzose, and seem to have been derived from lands to the east. They have been thoroughly indurated by cementation, so that the formation is exceedingly obdurate. The outcropping edges of its tilted beds constitute the crest of the Kittatinny range in New Jersey, and its continuations in New York and Pennsylvania. Silurian rocks have been recognized recently among the gneisses of Connecticut.

The Helderberg formation, formerly regarded as a part of the Silurian system, is here classed with the Devonian.

Silurian of the West

At various points in the West, there is a series of sedimentary beds, poor in fossils, between the known Ordovician below and the Devonian above. The character of the fossils being indecisive,

¹ Hartnagle, Bull. 107, N. Y. State Mus.

the age of the beds is open to question. Soje of them may be Silurian. If the Silurian is really absent from all the areas where its presence is not now known, it would appear that a large part of western North America was land during the Silurian period. Silurian beds are however known in Southern California, Nevada, Utah, and Alaska, and perhaps in the Canadian Rockies, and its distribution may be more widespread than has been supposed.

Summary

As in the case of all preceding systems of the Paleozoic, the greatest thicknesses of Silurian strata (estimated at about 5,000 feet, maximum) occur in the Appalachian mountain region. Over the interior, the system is relatively thin, being measured by hundreds of feet rather than thousands. In keeping with these variations, the system is largely of elastic sediments of shallow-water origin in the Appalachian belt, while in the interior it is largely of limestone. The site of sedimentation in the east was a sort of trough (the Appalachian trough) shut off from free communication with the interior sea, but connected with the Atlantic, perhaps by way of the present Chesapeake region. Since most of the sediments of this trough were deposited in shallow-water, they are usually thought to indicate that the trough was sinking at a rate comparable to that at which the sediments accumulated. This view may, however, need to be qualified as suggested on page 461. So far as sinking took place, the thick sediments may have been its cause, or one of its causes. With the down-warping of the trough, there may have been up-warping of the adjacent land area which supplied the sediments.

The history of the Silurian period, as now understood, involves, (1) a general submergence of the eastern part of the United States west of Appalachia, by which the sea became more and more widespread until the close of the Niagaran epoch; (2) a partial withdrawal of the sea from the same area during the Salina epoch; and (3) an extension of the sea at the close of that epoch. There were doubtless many minor oscillations of level which have not been determined.

Former extent and general stratigraphy. The present margins of the several Silurian formations are not their original margins,

for their exposed parts have suffered erosion, and the erosion of dipping beds shifts their outcrops. In some localities there are data for estimating something of the former extension of the formations. In Wisconsin, for example, remnants (outliers, *a*, *b*, *c*, Fig. 399) of the Niagara are found far beyond the main body of the formation as it now exists. These outliers fix at least a minimum limit to the original extension of the formation.

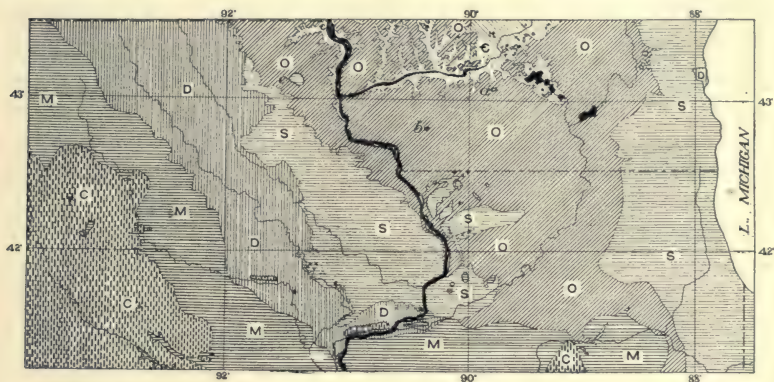


Fig. 399.—Map showing the surface distribution of Silurian, Ordovician, and other formations in southern Wisconsin, northern Illinois, and eastern Iowa. *C* = Cambrian; *O* = Ordovician; *S* = Niagara, and *a*, *b*, *c* are outliers of *S*; *M* = Mississippian; and *C* = Carboniferous.

Igneous rocks. At few points in North America have igneous rocks of Silurian age been identified. The Silurian formations are sometimes affected by igneous intrusions, but the date of the intrusions is generally uncertain. Some of the igneous rocks of New Brunswick are thought to be of Silurian age, and perhaps some of those of Nova Scotia and Maine.¹

Close of the period. The geographic changes at the close of the Silurian were less than those at the close of the Ordovician, and the Silurian system is perhaps less distinctly separated from the Devonian above than from the Ordovician below.

Climate and duration. There is nothing to indicate great diversity of temperature in the Silurian period, and much to suggest

¹ Williams, H. S., Jour. of Geol., Vol. II, pp. 16–18, and Penobscot and Rockland folios, U. S. Geol. Surv.

that uniformity extended through great ranges of latitude, for the fossils of warm-temperate regions are in part the same as those in Arctic regions. Some regions appear to have been temporarily very arid. The Silurian period was perhaps comparable in duration to the Ordovician.

Foreign Silurian

In Europe the Silurian strata have a distribution similar to that of the Ordovician, though they are wanting in some regions where the latter are present. The fact that the Silurian strata do not appear at the surface over wide areas does not indicate their general absence, so much as their wide-spread concealment. In most of the northern part of Europe, outside of Britain, the system has been little deformed. In the southern part of the continent, the Silurian formations appear in small areas only amidst formations of lesser age. In contrast with the Silurian rocks of the northern province, those of the southern are much deformed.

The Silurian formations of Europe, especially of the northern province, are more largely composed of limestone than those of the Ordovician, suggesting clearer seas.

Geographic changes took place in Europe at the close of the period as shown by the unconformity between the Silurian and Devonian systems in some places (Great Britain and Ireland), though conformity is the rule.

The Ordovician and Silurian of other continents have not been generally distinguished. The equivalents of the two systems as distinguished in Europe and North America probably occur in all the less well-known continents.

THE SILURIAN LIFE

The extensive withdrawal of the sea from the surface of North America at the close of the Ordovician period reduced the area of shallow-sea water available for the life which needed it. The severe repressive evolution which followed was the great biological feature of the transition from the Ordovician to the Silurian. With the re-invasion of the interior by the mid-Silurian sea, there followed an expansional evolution of the shallow-water fauna, which constitutes the great biological feature of the middle of the period. Toward the close of the period there was another restriction of the

epicontinental sea, complicated with intense salinity in the eastern interior region, and there followed a second repressive evolution by which the fauna passed into the Devonian type.

Theoretically, the history of the land life should have been the reciprocal of that of the sea; for as the sea contracted, the land expanded, and an expansional evolution of land life should have run hand in hand with the restrictional evolution of the sea life. This was probably the fact, but the record of the land life is too meager to demonstrate it. In so far as the climate was arid, it was unfavorable for abundant land life.

The Transition from the Ordovician

Of the shallow-water life of the early Silurian there is but meager record. The eastern shore of the continent was then far out on the borders of the continental platform, and the deposits there are buried and inaccessible. The western border may have been submerged, but the fauna there is little known.

Aside from the lessened area favorable for shallow-water life, the conditions were probably less favorable, area for area, than before, for the wash from the land was presumably increased. The increased detritus brought to the sea probably inhibited some forms of life, injured others, and helped but a few. Some of the basins and bays were doubtless too fresh and some too salt, and some may have varied unfavorably in salinity. These general considerations may explain the meagerness of the faunas of the early Silurian strata. But conditions were not adverse everywhere. In the Gulf of St. Lawrence, Ordovician species lived on for varying lengths of time, and mingled with Silurian species as they developed, and so recorded the transition. This appears to have been the breeding-ground of one of the provincial phases of the Silurian fauna, but it is not probable that it was the only one. The main Silurian fauna of the interior apparently did not spring from that of the Atlantic border, but developed somewhere at the north, or migrated from Europe by a northerly route.

The Expansional Stage and the Mid-Silurian Fauna

As the sea slowly overspread the continent toward the middle of the period, increasing room and more congenial conditions for

most forms of shallow-water life resulted in an expansional evolution which produced the Niagara fauna. The families and classes were much the same as in the Ordovician period, but most of the genera were new, and nearly all the species. In general there was a biological advance, though this was not true of all classes. Only the more conspicuous features of the changes will be noted.

The echinoderms. A distinguishing feature of the Silurian fauna was the rich and varied development of the echinoderms, involving at once the rise or the decline of previous forms, and the introduction of new ones. The great feature of the period, in connection with the echinoderms, was the rise of the *crinoids*. They attained such abundance in certain congenial localities that their fragments formed the larger part of the limestone. These spots were veritable "flower-beds" of "stone lilies," where beautiful and varied forms grew in groves, as it were. The assemblage of species at each of these localities had its own peculiarities, but the genera were the same or similar. A few Silurian crinoids are shown in Fig. 400, but no limited number of figures can do justice to their variety and beauty. Notwithstanding various signs of progress, many of the more primitive characters remained, indicating that the class had not yet reached its climax.

Cystoids were still abundant, and the true blastoids now appear for the first time. *Starfishes* appear to have made little progress and to have had no large place in the fauna, and the serpent-stars and the echinoids had even less. The slow development of these types which were prominent much later, possibly represents a general fact, viz., that great classes were really slow in their evolution, however suddenly they may seem to have come into existence. Perhaps the ascent of the cystoids and crinoids to their climaxes would be found to be as slow as those of their kin, if we could trace their history back to its beginning. A little greater imperfection in the fossil record would have eliminated all trace of the serpent-stars and sea-urchins in these early periods, and would have made their appearance in abundance at a later period seem sudden and remarkable.

The brachiopods. The brachiopods stood the vicissitudes of the passage from the Ordovician to the Silurian with no loss of prestige,

though they suffered an almost entire change of species and a very large change of genera. When it is considered that the brachiopods were among the most resistant and conservative of the invertebrates, this large change of species and genera emphasizes the

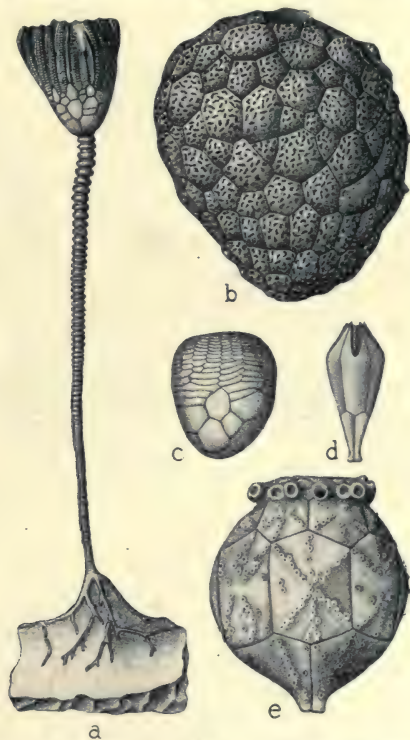


Fig. 400.—*Silurian Echinoderms*: *a*, *Eucalyptocrinus crassus* Hall, a complete crinoid, showing roots, stem, and body; *b*, *Holocystites adiapatatus* Miller, a cystoid with irregularly arranged plates and scattered pores; *c*, *Lecanocrinus macropetalus* Hall, an articulate crinoid; *d*, *Troostocrinus reinwardtii* (Troost), showing the typical bud-like form of a blastoid; *e*, *Caryocrinus ornatus* Say, a cystoid with regularly arranged body plates. Pores in radiating lines from centers of plates.

stress of the conditions that controlled the transition, and its biologic importance. The Silurian brachiopods had gained in differentiation, and had made some notable advances in structure. On the whole they were more robust and gave more obvious signs of

abounding vitality than before; but along with the progressive developments there were some retrograde modifications.

The bryozoans. The coral-like bryozoans contributed much less to the Silurian limestones than to those of the preceding period. This was partly because the class had declined, and partly because

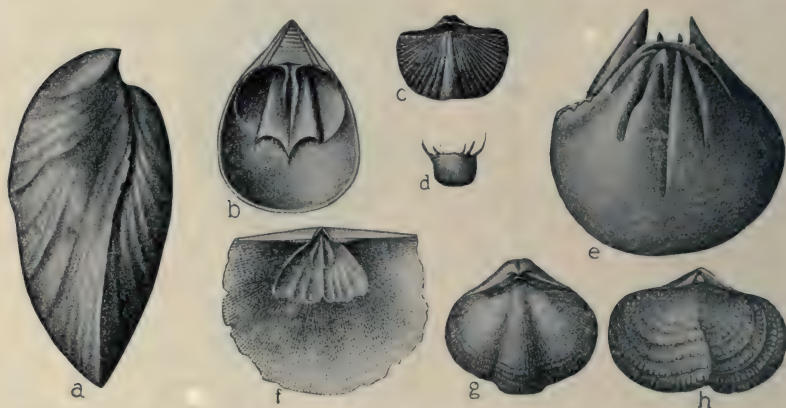


Fig. 401.—*Silurian Brachiopods*: *a*, *Pentamerus oblongus* Murch., lateral view of an interior cost; *b*, *Trimerella acuminata* Bill., the interior view of a pedicle or ventral valve, showing the elevated platform for muscular attachment excavated beneath; *c*, *Spirifer niagarensis* (Con.), exterior view of the brachial or dorsal valve, with the cardinal area and beak of the pedicle valve showing above; *d*, *Chonetes cornutus* (Hall), exterior view of ventral valve, showing the cardinal spines; *e*, *Trimerella ohioensis* Meek, the internal cast of a highly differentiated inarticulate brachiopod, showing the finger-like casts of the excavations beneath the elevated muscular platforms; *f*, *Stropheodonta profunda* Hall, interior of the ventral valve, showing muscular impressions; *g*, *Spirifer radiatus* Sow.; *h*, *Streptis grayi* (Dav.), exterior view of the brachial valve, showing the cardinal area and beak of the opposite valve, and the peculiar twisted form of the shell.

the more massive types were replaced largely by more delicate and fragile forms.

The mollusks. The *cephalopods* appear to have remained the most powerful inhabitants of the seas. The straight forms were still common, but curved and coiled ones were more numerous. Their shells were more highly ornamented than before, but they were still plain in comparison with some of their successors. The apertures of the shells of the Ordovician species were usually circu-

lar or oval, but in the Silurian species many of them were curiously constricted (*b*, Fig. 402), especially among the small curved and coiled species. The constriction appears to have been a protective device.

Although the *gastropods* were fairly well represented in the Cambrian period, and amply in the Ordovician, they did not increase greatly in the Silurian. They show advance in the preponderance

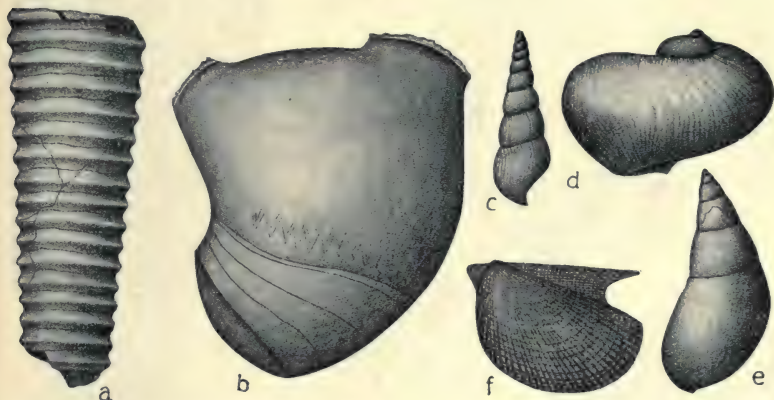


Fig. 402.—*Silurian Mollusks*: *a* and *b* are cephalopods. *a*, *Orthoceras annulatum* Sow., a straight chambered shell with annulations; *b*, *Phragmoceras nestor* Hall, lateral view of a curved chambered shell with peculiar constricted aperture. *c*, *d*, and *e* are gastropods; *c*, *Loxonema leda* Hall; *d*, *Platystoma niagarensis* Hall; *e*, *Subulites ventricocus* Hall; *f*, *Pterinea emacerata* (Con.), exterior view of left valve of a pelecypod.

of elevated spires, in increased variety of form, and some of them in greater size; but the older types were still plentiful.

The *pelecypods* (*f*, Fig. 402) were not so well represented in the mid-Silurian beds as in the Ordovician, perhaps because the calcareous bottoms were less congenial to them.

Corals. The prominence gained by the corals in suitable situations is one of the notable features of the Silurian fauna. In the Ordovician period, the simple forms predominated over the compound. The ratio was now reversed. Among the notable types was the unique chain coral (*Halysites*, Fig. 403, *c*), which had appeared in the Ordovician; the honeycomb coral (*Favosites*, *a*);

the organ-pipe coral (*Syringopora*, *b*); and the cup coral (*Zaphrentis*, *e*). A most peculiar coral of the simple class (*Goniophyllum*, *d*) was quadrangular, and its top provided with a cover (operculum) of four triangular plates hinged to the four sides of the cup's margin.

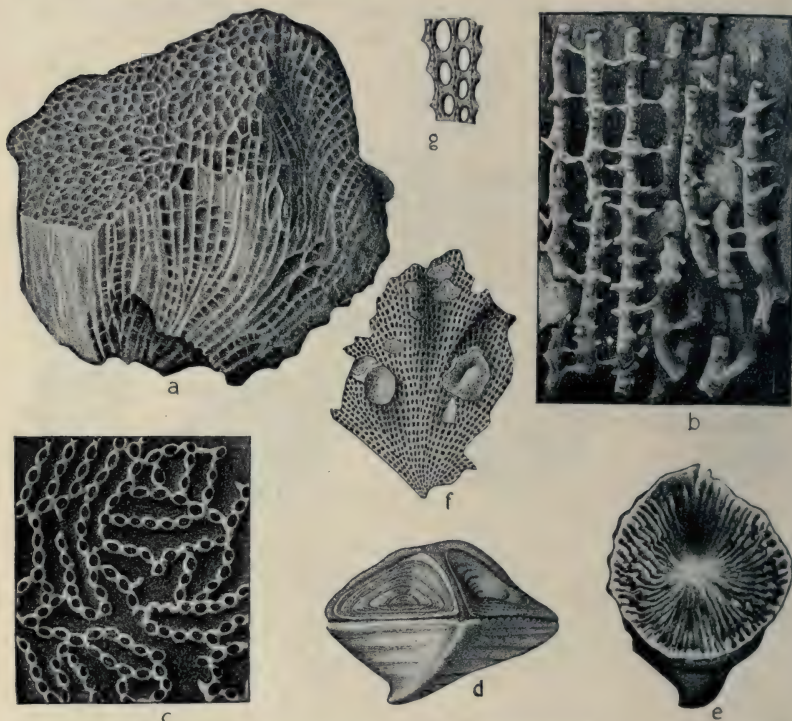


Fig. 403.—*Silurian Corals and Bryozoans*: *a-e* are corals. *a*, *Favosites occidentis* Whit.; *b*, *Syringopora verticillata* Goldf.; *c*, *Halysites catenulatus* Linn.; *d*, *Goniophyllum pyramidale* (His.); *e*, *Zaphrentis umbonata* Roming. Bryozoans, *f* and *g*, *Fenestella parvulipora* Hall.

When closed they formed a pyramid over the cup (*d*, Fig. 403, only two of the opercular plates shown). This was a protective device unknown among modern corals.

With their increase in abundance, the corals acquired the habit of associating themselves together. This resulted in the formation of reefs. The known reefs appear to have been formed some

distance from shore, and to have been of the barrier type. The reef-forming habit appears to have been local rather than general, for over large tracts corals are found scattered in a markedly distributive fashion.

The trilobites. No new families of trilobites appeared, though some new genera were added and many species; but these did not offset the disappearance of old ones, and the class, though still

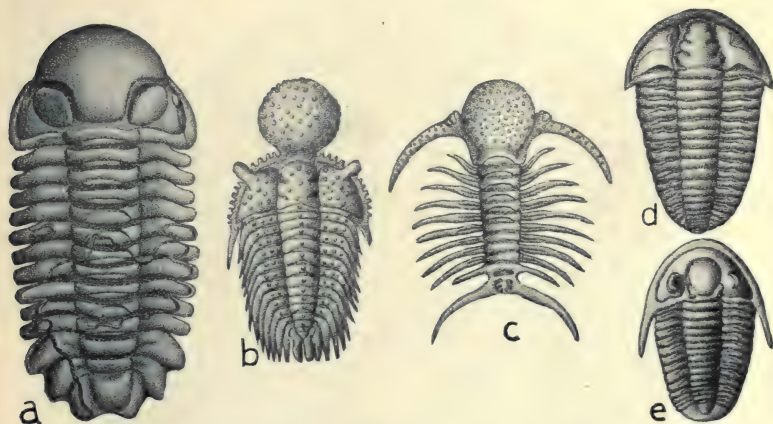


Fig. 404. *Silurian Trilobites*: a, *Sphaerexochus mirus* Bey., dorsal view; b, *Staurocephalus murchisoni* Barr, dorsal view, showing the peculiar globular anterior prolongation of the head; c, *Deiphon forbesi* Barr, dorsal view of a peculiar trilobite having the pleural lobes much reduced; d, *Calymene niagarensis* Hall, dorsal view of one of the commonest Silurian trilobites; e, *Cyphaspis christyi* Hall, dorsal view.

important, had already entered upon its decline numerically. The highest forms were, however, structurally equal, and perhaps superior, to any that preceded.

Other marine invertebrates. *Sponges* flourished. There was a prolific field of them in western Tennessee, where the conditions were not only congenial to their growth, but favorable for their preservation. The peculiar *Receptaculites* family (Fig. 405). whose affinities were long in doubt, was still present, though its climax was passed. The *graptolites* had lost the importance they had in Ordovician times, and by the end of the period neared extinction.

Sea-worms are recognized through their jaws, tracks, and burrows, and by the calcareous tubes which some of them secreted.

The vertebrates. In the earlier and mid-Silurian deposits few relics of fishes have been found, and these few are very imperfect; but in the upper part of the system their remains are not rare.

Marine plants. Knowledge of marine plant life remains, as before, unsatisfactory. While theoretically it must have been



Fig. 405.—*Receptaculites oweni* Hall; "lead coral" or "sunflower;" original $9\frac{1}{4}$ inches in diameter.

abundant, only obscure markings of the fucoidal type and a few evidences of higher forms have been found, and their interpretation is more or less doubtful.

Foreign Faunas and Migrations

Deferring the consideration of the peculiar closing fauna for a moment, the relations of this rich and varied mid-Silurian assemblage may be noted. The general progress of life on other continents, so far as known, was similar to that on the American, but

perhaps less pronounced and symmetrical. Where the forms on different continents were merely similar, it is at present an open question whether the similarity was due to intermigration, or to independent evolution along similar lines; but where the forms on separate continents are identical, especially if the species are peculiar and aberrant, it may be assumed that they had a common origin, and that migration is indicated. A striking case of this kind is presented by the quadrangular operculated coral already mentioned (Fig. 403, *d*), which is found with identical idiosyncrasies in the island of Gotland in the Baltic Sea, and in Iowa. The evidence of migration is strengthened by the presence in Gotland of three or more peculiar genera of crinoids that are found also in the upper Mississippi basin. Besides such special cases, many prominent and familiar species were common to America and Europe, and some of them are also found in Asia, Australia, and New Zealand. Migratory connections between North America and these lands may therefore be assumed. Since thirty or more species are known to be common to North America and Europe (the interior of North America and Sweden and Great Britain), and since these embrace a wide range of genera of very different habits, there is a strong presumption of migration between North America and northwestern Europe.

It has already been stated that the interior sea of North America seems to have had no free communication with the sea to the east or south, and that its extension far to the west is doubtful. To the northward, on the other hand, the series of remnants of Silurian formations, probably once connected, point to a broad thoroughfare for shallow-water life between North America and Europe by way of Greenland.

The faunas that occupied the Appalachian trough, the St. Lawrence embayment, and the Atlantic coast appear to have had but limited connection with the fauna of the interior during the mid-Silurian epoch. In the present state of knowledge, the faunas of the Appalachian trough bear the aspect of provincialism.

The Closing Restrictional Stage

Following the luxuriant life of the mid-Silurian epoch, there came, in North America at least, a notable decline, due to the

withdrawal of the epicontinental waters from the larger part of the interior, and to the conversion of the remainder into an excessively salt sea, in the deposits of which few fossils are found. The Waterlime beds represent a gradual return in the Salina basin of conditions hospitable to life. The fauna of these beds is limited, but radically unlike that of the Niagaran epoch. Most of the

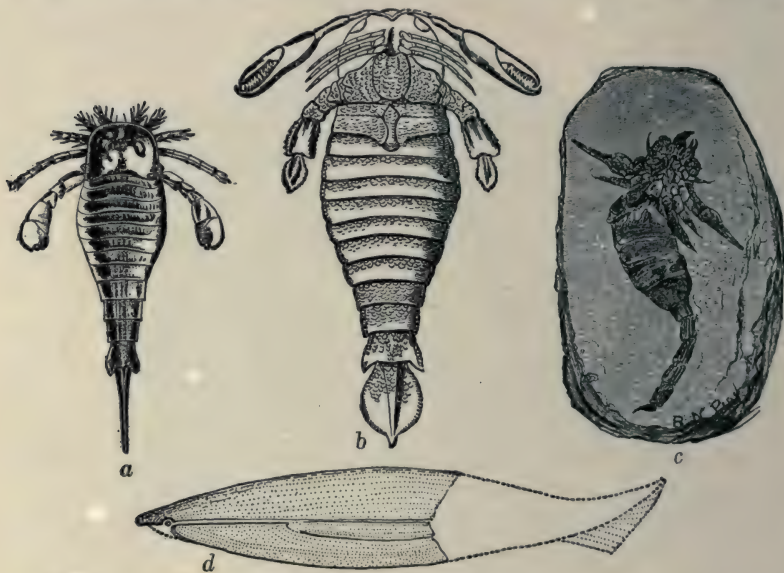


Fig. 406.—Crustaceans other than Trilobites (a, b and c), and Fish (d): a, *Eurypterus fischeri* Eich., restoration after Schmidt; b, *Pterogotus anglicus* Agass., restoration after Woodward; c, *Palæophonus caledonicus* Hunter, after Peach; d, *Palæaspis americana* Claypole, restoration by Claypole, modified by Dean.

familiar marine types are absent from the later fauna, and its signal feature was an abundance of large crustaceans of types barely represented before. The most characteristic of these were the great *Eurypterus* (Fig 406, a) and the still more gigantic *Pterogotus* (b). The former reached a length of a foot and a half or more, and the latter attained a length of over six feet in the next period. These were gigantic dimensions for crustaceans, and were probably never surpassed. These giants among their kind seem clearly to

have been aquatic, but whether they were inhabitants of salt or fresh water is not obvious. They are wholly extinct, and their habitat can only be inferred from their associations. In England, Sweden, and Russia, eurypterids are associated with marine fossils, but they are also associated with the seeds of land plants and with fish which, in the succeeding stage, seem to have occupied land waters chiefly. In the Devonian and Carboniferous periods, eurypterids are associated with land plants, scorpions, insects, fishes, and fresh-water amphibians, which seem to imply a fresh-water habitat. In the light of these facts, the more common inference has been that they were originally marine forms, and became adapted later to brackish- and fresh-water conditions. An alternative inference is that they were originally denizens of the land waters, and that their remains were sometimes carried out to sea by streams, and thus fossilized with marine forms. Mollusks, crinoids, corals, and similar marine forms are almost entirely absent from the fauna of the Waterlime. The few brachiopods found are usually pauperitic, as though they lived in uncongenial conditions. The occasional presence of a few undoubted marine forms does not so much indicate that the waters were habitually saline, as that they were occasionally and partially so.

It is at this time also that the earliest known *scorpions* appeared both in America and Europe. They were allied to the eurypterids. The European forms have been thought to be land species, though this has been questioned. The sting and the poison glands have been identified, and the significant name, *Palæophonos*, "ancient murderer," applied in consequence (Fig. 406, c). The American species have been thought to be aquatic.

The presence of *fishes* emphasizes the peculiarities of this fauna. Except for their occurrence at a few points in the Rocky Mountains in the Ordovician, fish remains have not been found in America until this stage. In Europe a few fishes appear somewhat earlier, but nearly all the fish remains of the period yet found are in the very highest horizons of the Silurian, or in the deposits that form the transition to the Devonian, where they are associated with eurypterids and land plants, as well as marine invertebrates. It would appear that the fishes of the time were varied, and that they were the fore-

runners of the abundant fishes of the Old Red Sandstone of the Devonian. As the sand of this formation was probably deposited by land waters, the association of the fish with eurypterids and land plants carries some further presumption that the peculiar crustacean fauna lived normally in land waters. It is not to be overlooked, however, that in the transition beds the fishes are also associated with marine fossils, and there is no question that, before the close of the Devonian period, certain fishes at least were truly marine.

Map work. See note at end of Chapter XVII, page 535.

CHAPTER XIX

THE DEVONIAN PERIOD

FORMATIONS AND PHYSICAL HISTORY

Early in the Devonian period, the sea covered the present area of land to some such extent as shown in Fig. 407. During the period, there were changes in the relations of land and water, some of which were of great importance in their effects on the life of the period.

The Devonian system, like its predecessors, is conveniently divided into a Lower, a Middle, and an Upper portion. The subdivisions now recognized in New York (the state where the Devonian is best developed and known) are as follows:

Devonian	Upper Devonian	Chautauquan	Chemung and Catskill
		Senećan	Portage beds
	Middle Devonian	Erian	Genesee shale
			Tully limestone
		Ulsterian	Hamilton shale
			Marcellus shale
			Onondaga (Corniferous limestone)
	Lower Devonian	Oriskanian	Schoharie grit
			Esopus grit
		Helderbergian	Oriskany beds
			Kingston beds
			Becraft limestone
			New Scotland beds
			Coeymans limestone

The subdivisions in the last two columns are not applicable in detail to regions remote from New York. Of the above formation names, Helderberg (or Helderbergian), Oriskany, Onondaga (Corniferous), Hamilton, Portage, and Chemung, have widest application

¹ As originally classified, there was a *Lower* and an *Upper* Helderberg formation. The latter is now more commonly known as the *Onondagan* (Corniferous). In this volume the term Helderberg is applied to the former only. The adjective "lower" therefore becomes superfluous.



Fig. 407.— Map of North America, showing the outcrops of the Helderberg formation and the general relations of land and water during the Helderberg epoch. The conventions are the same as in the earlier maps of the series.

outside the state, but other local names are used instead of these in many places.

Devonian of the East

The Lower Devonian. The known *Helderbergian series* is confined largely to the eastern part of the continent. It is known (1) in Maine and farther northeast, (2) in the Appalachian belt, and (3) in the lower Mississippi basin (Fig. 407). It is largely limestone, 300 to 600 feet thick in eastern New York and Pennsylvania, but thinner to the west.

The *Oriskany formation* is best known in the northern Appalachian region, but beds of the same age have a wide though not well determined distribution farther west. They are also present in the northeast (Gaspé, New Brunswick, and Nova Scotia). Where best known, the Oriskany is made up chiefly of coarse sandstone. From the vicinity of Cumberland, Md., where the formation has a thickness of a few hundred feet, it thins to the northeast and the southwest, and loses its most distinctive faunal characteristics.

The Middle Devonian. The most important formations of the Middle Devonian are the Onondaga and Hamilton, which are more wide-spread than the Lower Devonian formations. In the east, the Onondaga formation is underlain by elastic beds (Esopus and Schoharie) the equivalents of which have not been differentiated with certainty west of the Appalachian region. They appear to be shore formations, and the lower beds of the Onondaga limestone may have been in process of deposition over the eastern interior while the Esopus and Schoharie beds were accumulating in the Appalachian belt. If this is the case, the conditions for limestone accumulation were presently extended eastward.

The *Onondaga limestone* is found from New York to the Mississippi (Fig. 408). It rests on Silurian beds,¹ often with little evidence of unconformity. The epicontinental sea in which the limestone was formed was relatively clear and shallow, as shown by the composition of the rock and the character of the fossils it contains. In many places the limestone is rich in coral, and locally the coral-reef structure is as perfectly shown as in the reefs of modern times. This is true, for example, at the rapids of the Ohio

¹ See Reports of Iowa, Missouri, Arkansas, Indiana, and Michigan.



Fig. 408.— Map of North America, showing the outcrops of the Onondaga formation, and the general relations of land and water during the Onondaga epoch. The Devonian at the northwest is not all Onondagan. Note the interrogation marks in the lower Mississippi valley.

near Louisville. The formation is not a thick one, rarely more than 100 to 200 feet.

The equivalent of the Ulsterian series occurs east of the Appalachians in northern New England and Canada, having a distribution similar to that of the Helderberg. The formation occurs also on the west side of James Bay (south end of Hudson Bay), and the remnants here may have been connected formerly with one another, and with the equivalent formation of the interior of the United States.¹ The distribution of such formations as this and the Niagara (p. 539) give some idea of the extent to which erosion has removed formations from regions which they once covered.

Following the Onondagan epoch of clear seas, conditions changed so as to give origin to deposits of mud where limestone had been accumulating. These mud beds and their equivalents, now consolidated, constitute the *Marcellus* and *Hamilton* formations of New York (p. 559). In the interior, the equivalents of the two formations are commonly grouped together under the name Hamilton, or given local names. In the east, shale is the most common rock, but in the west, there is a good deal of limestone.

Considerable areas in the southern and northwestern parts of the Mississippi basin which had been land in the earlier part of the period appear to have been submerged in this epoch, for the Hamilton formation probably overlaps its predecessor in these directions, resting on Silurian beds. The spread of the sea at this time, beginning perhaps a little earlier, appears to have submerged areas in the south (southern Appalachians and areas farther west) which had been land since the close of the Ordovician, and perhaps opened up connection between the interior sea and the Gulf of Mexico, allowing shallow-water species of animals to migrate into the Mississippi basin from the south. The Cincinnati arch may have been land throughout the Hamilton epoch, though this cannot be affirmed. If the Hamilton formation once overspread this arch, it has been removed.

The conditions for the origin of the Hamilton shales would seem to be met if the surrounding lands (Appalachia and lands north of the interior sea), after standing low while the Onondaga limestone

¹ Weller, Jour. Geol., Vol. X, pp. 423-432.



Fig. 409.—Map of North America showing the outcrops of the Hamilton formation and the general relations of land and water during the Hamilton epoch. The black area at the north probably includes Lower and Upper Devonian as well as Middle. Compare Figs. 407 and 408. The conventions are the same as in earlier maps.

was making, were more elevated, or less protected by vegetation, or subjected to more concentrated or spasmodic precipitation during the Hamilton epoch. Under the earlier conditions, the land formations would have been undergoing decay, but the products of the decay might not have been removed; under the latter, there would have been opportunity for the transportation of the products of decay. Even during the general period of shale formation, however, limestone (often shaly) was making in some places, as in the Mississippi basin.

In the east, the Hamilton (including Marcellus) formation is very thick, being 1,500 to 5,000 feet thick in Pennsylvania, where it is mainly clastic. Its thickness over the interior, where it contains more limestone, is much less.

The Upper Devonian. The Upper Devonian series has a distribution (Fig. 410) similar to that of the Middle, though it is more wide-spread, especially west of the Mississippi. On the whole, the Upper Devonian is more distinct from the Middle than the Middle is from the Lower, and is somewhat closely connected with the lower part of the succeeding system. An unconformity appears at the base of the Upper Devonian in some places, and the series overlaps all other Devonian formations, resting on Ordovician beds in others.¹

The Senecan series of New York consists of various thin marine formations (p. 559), chiefly clastic, all of which bear evidence of shallow-water origin.

The Chautauquan series possesses some exceptional features. The *Chemung formation* of New York is very like the Portage, though more sandy, and even conglomeratic locally. It ranges in thickness from 950 feet near Lake Erie, to 1,500 feet in the vicinity of Cayuga Lake. Much greater thicknesses are attained in Pennsylvania, but to the westward the formation thins rapidly.

In the Catskill region, there is a series of red shales and sandstones, the *Catskill formation*, which appear to be, in a general way, the time-equivalents of the Chemung. In some places the Catskill

¹Ulrich has recently proposed grouping the Upper Devonian with the lower part of the Mississippian, as a new system, under the name of Tennessean. Geol. Soc. Am., Dec., '08.

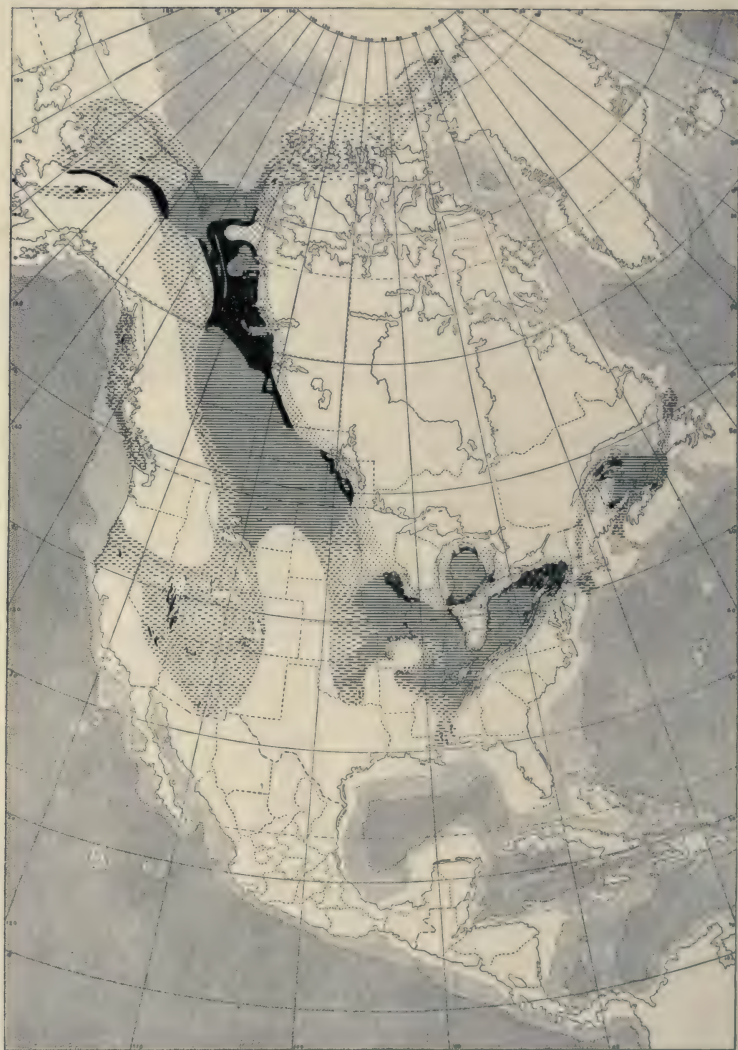


Fig. 410.— Map of North America, showing the outcrops of the Upper Devonian formations, and the general relations of land and water in late Devonian time. The conventions are the same as in earlier maps (see p. 477). (See note under Fig. 409, concerning the Devonian in the northwest. Note also the interrogation marks in the lower Mississippi basin.)

beds may represent less than the full Upper Devonian, and in others more. The Catskill formation is poor in fossils, and such as occur are partly, if not wholly, of fresh- and brackish-water forms. Hence it is inferred that the Catskill region was so far shut off from the ocean as not to afford the conditions necessary for marine life. The redness of the formation is a feature which marks many other formations made in inclosed or partially inclosed basins.

The Catskill formation has a thickness of 3,000 feet in New York and twice that amount in Pennsylvania. Local beds of sandstone (the Oneonta of central New York), seemingly like the Catskill in origin, occur outside the Catskill region, suggesting that similar conditions of deposition existed now and then farther west.

The thickness of the Upper Devonian in central and western New York approaches 4,000 feet, and is even more in Pennsylvania and Maryland.¹ In Ohio the same series (Black, or Ohio shale²) has a maximum thickness of 2,600 feet, and thins notably to the north and west, being but a few hundred, and often but a few score feet thick in Indiana, Illinois, Iowa, southern Michigan, Kentucky, and Tennessee. Diverse names are applied to the series and its subdivisions in various localities.

Although the implication of the preceding paragraphs is that the Devonian formations of the East are chiefly marine, it should be added that some of the formations, as the Portage and some of the beds of Maine, contain considerable numbers of land plants, and are presumably, not altogether marine.

West of New York and Pennsylvania the Upper Devonian beds have few commonly recognized subdivisions, or, in most places, none at all, and the eastern names are not in general use.

Devonian of the West

The Devonian system, so far as known, is absent from the larger part of the Great Plains within the United States, and this great expanse of territory was probably land during the period. No Devonian beds are found about the older formations in Dakota

¹ Prosser, Jour. Geol., Vol. IX, pp. 415-442. This article is a concise summary of the Paleozoic systems of Maryland.

² Geol. Surv. of Ohio.

or Wyoming, in those places where the succession of formations has been studied in detail. The Helderberg is present in the Arbuckle Mountains of Oklahoma,¹ and probably in southwestern Texas.² The Devonian system has little development in the Rocky Mountains, but is somewhat wide-spread between the Rockies and the Sierras, though its outcrops are not extensive. In some places, as about Globe, Arizona, the system is much faulted and affected by igneous rock;³ in others it is bounded by unconformities, both below and above,⁴ while in still others its limits are not sharply defined. The system in the west has not been generally subdivided, and where subdivisions have been made, they have not been correlated with those of the east. In the Great Basin region, Onondagan types of fossils are found, and in overlying beds, fossils corresponding to the Eurasian (rather than to the east American) faunas, have been recognized. Hamilton types, with great vertical range, also occur. The testimony of the fossils of the Basin region is to the effect that it was not connected with the eastern interior sea in such a way as to allow the free intermigration of marine life.

The system is said to be 8,000 feet thick in parts of Nevada,⁵ and 2,400 feet in the Wasatch Mountains; but in the Yellowstone Park,⁶ it is only 160 feet thick, and not divisible into distinct formations. In the western interior generally, limestone is the dominant formation.

Devonian formations are known in both northern and southern California, and may be present in many places where the rocks are metamorphosed past identification. In the Klamath Mountains, the Devonian (chiefly Middle) is much disturbed, and contains igneous rocks (tuffs and lava flows). The Devonian system is also

¹ Taff, Atoka (I. T.) folio, U. S. Geol. Surv.

² Hill, Physical Geography of the Texas Region, folio 3, topographic atlas, U. S. Geol. Surv., p. 4.

³ Ransome, Professional Paper, No. 12, and Bisbee folio, U. S. Geol. Surv., pp. 39-46; also Reagan, Am. Geol., Vol. XXXII, p. 278.

⁴ Walcott, Am. Jour. Sci., Vol. XXVI, p. 437, 1883.

⁵ Geol. Expl. of the 40th Parallel, Vol. I; see also Weller, Jour. Geol., Vol. X, pp. 423-432.

⁶ Weed, Yellowstone Nat. Park folio, U. S. Geol. Surv.

abundantly represented in widely separated parts of Alaska.¹ The Devonian faunas of the coastal region, like those of the Great Basin, are Eurasian in their affinities.

Middle Devonian in the northwest. A considerable area of Devonian which has sometimes been called Hamilton is found in the basin of the Mackenzie River and southward to Manitoba.² The great arm of the sea in which the Devonian of this area accumulated appears to have extended as far south as northern Missouri (Fig. 409). Whether this arm of the sea antedated the Hamilton epoch is uncertain.

The fossils of this northwestern Devonian are different from those of the Hamilton formation of the east (Illinois to New York), and if the beds of the two regions were contemporaneous, as they may have been, they seem to have been deposited in waters which were not connected. The union was probably prevented by a narrow belt of land running south-southwest from Wisconsin to Missouri, somewhat as shown in Fig. 409. Till late in the Hamilton, this land seems to have constituted a barrier between the eastern interior sea and a northwestern sea which stretched from Missouri on the southeast, through the Mackenzie basin to the Arctic Ocean on the north. Toward the end of the Hamilton epoch, this barrier seems to have been removed sufficiently to allow the waters and the life on opposite sides to mingle freely.

Areas Where the Devonian Comes to the Surface

While the Devonian system is widely distributed it does not appear at the surface over large areas. The reasons for its limited exposures are substantially the same as those for the limited exposures of earlier systems, and have been explained.

The absence of the Devonian strata in certain situations is significant. Thus between Iowa and Indiana, Devonian formations do not appear at the surface between the Silurian on the north and the Carboniferous on the south. The absence of Devonian beds

¹ Brooks, Bull. Geol. Soc. Am., Vol. XIII, pp. 256-261, and Professional Paper, No. 1, U. S. Geol. Surv., p. 211; Schrader, Bull. Geol. Soc. Am., Vol. XIII, p. 241; and Professional Paper, No. 20, U. S. Geol. Surv., pp. 62-67.

²Whiteaves, Am. Geol., Vol. XXIV, 1898, pp. 210-240.

here might indicate either that the deposits of the Carboniferous period extended farther north than those of the Devonian, concealing the latter, or that Devonian beds, once deposited north of the present border of the Carboniferous system, were worn away before the deposition of the latter. Of these alternatives the latter is probably correct, for near Chicago a small remnant of Devonian sediment has been found in a fissure in the Niagara limestone, as illustrated by Fig. 411. The limestone was apparently fissured



Fig. 411.—Figure illustrating the occurrence of remnants of Devonian material in fissures in Niagara limestone, near Elmhurst (Cook Co.), Illinois.

before the Devonian sediments were deposited upon it. Portions of the sediments fell into an open fissure, carrying with them distinctive fossils (fish teeth). In this protected position, the fossils escaped removal.

Igneous rocks. Igneous rocks have little representation in most parts of the well-known Devonian of the continent, but in Nova Scotia, New Brunswick, and Maine, and at some points in the west, there are igneous rocks which appear to be of Devonian age. In many places in the west, the Devonian strata have been affected by dikes and intrusions of later times.

Duration. The Devonian period was probably one of the shorter periods of the Paleozoic, though its duration cannot now be stated more definitely.

Close of the Devonian

The general period of quiet which had prevailed during the period seems not to have come to an end at its close. Only in the eastern part of the continent, in Maine, Nova Scotia, New Brunswick, and the adjacent region to the north do the Devonian strata appear to have been notably disturbed at the close of the period. Here they are overlain unconformably by the Lower Carboniferous. Elsewhere the formations of the younger system rest on those of the older without stratigraphic break. There is, indeed, some reason for associating the Upper Devonian, as here outlined, with the succeeding system.

Economic Products

Gas and oil. The Upper Devonian is the chief source of oil and gas in western Pennsylvania¹ and southwestern New York, and is one of the sources in West Virginia.² The Middle Devonian is the oil-producing series of Ontario. Within the regions of their occurrence, oil and gas are more likely to be found under low anticlines than in other positions, apparently for the reason that anticlines furnish an inverted basin capable of holding these light substances against the pressure of the heavier subterranean water



Fig. 412.—Section showing the relations of the Devonian and other Paleozoic systems in the vicinity of Loudon, Tenn. C = Cambrian; O Ordovician; S = Silurian; D = Devonian; au = age unknown. Length of section, about 7 miles. (Keith, U. S. Geol. Surv.)

which tends to force them to the surface. In all cases there must apparently be an impervious bed or combination of formations above, to prevent the escape of the oil and gas. In this there is a certain similarity to the conditions requisite for artesian wells, but with the difference that the artesian wells receive their supplies from above and must be closed below, while the oil and gas wells receive their supplies from below and must be closed above.

The lower part of the Chattanooga shale of central Tennessee is the horizon of black phosphates, which are of some importance commercially.³

THE FOREIGN DEVONIAN

The continent of Europe. At the close of the Silurian there seem to have been more considerable geographic changes in Europe than in America, for the Devonian system is there more commonly

¹ Carll, Rept. I, 5, Penn. Geol. Surv., 1890. For statistics on the production of oil, gas, etc., see Mineral Resources of the United States, an annual publication of the U. S. Geol. Surv.

² White, West Virginia Geol. Surv., Vol. I, Oil and Gas, pp. 208 and 212. This volume is an important contribution to the literature of oil and gas.

³ Columbia (Tenn.) folio, U. S. Geol. Surv.

unconformable on its base. This is especially true in the north-western part of the continent.

During the progress of the period, the European continent was progressively submerged, for the Middle and Upper Devonian formations are more wide-spread than the Lower (Fig. 413). In this respect, the phenomena of Europe are in partial correspondence with those of America, though the overlap of the Middle and Upper Devonian of Europe is greater than in America.

The British Isles. In the British Isles the Devonian system has two phases. The first is found in southwestern England in the area which gave the system its name (Devonshire). The system here is thick and of marine origin. Igneous rocks are often associated with the sedimentary. Valuable ore-bearing veins occur, as in Devon and Cornwall.

The second phase of the Devonian is the *Old Red Sandstone*, widely distributed in Great Britain and Ireland and found at some points on the continent. Concerning the history of this Sandstone there has been much difference of opinion, but it is commonly held to have been deposited in a series of inclosed or nearly inclosed basins containing lakes or inland seas, the waters of which were fresh or brackish. It is further believed that crustal warpings gave the sea occasional access to these basins. In general the strata are poor in fossils. Some of those present are fresh-water species, and others are land species; but marine species occur at some horizons. It is not improbable that some parts of this singular sandstone are of subaërial, rather than subaqueous origin. The Old Red Sandstone has some features like those of the Catskill formation of America.

The Old Red Sandstone of the British Isles has at its maximum a thickness of more than 20,000 feet,¹ but this includes much igneous rock. There is an unconformity in the series, and the upper division contains conglomerates of such a character as to have raised a question concerning the existence of glaciers in Great Britain in Devonian times.

West central Europe. The Devonian of Germany is remarkable for the proportion of igneous rock interbedded with the sedimen-

¹ See notes concerning such thicknesses, p. 461.

taries. The igneous rock occurs in many separate beds, showing that there were many periods of igneous activity separated by intervals of quiet. In much of central-western Europe the Devonian strata have been metamorphosed, and their structure is often complex. In not a few places, especially where the sedimentary rocks have been invaded by igneous rocks, mineral veins have been developed, and from them large quantities of iron, tin, copper, and other metals have been obtained.¹



Fig. 413.—Sketch map of Europe during the Devonian. The horizontal lines represent the Lower Devonian; the vertical lines mark the additional areas where the Middle Devonian occurs. (After DeLapparent.)

Russia. The Devonian of Russia is made up of beds of arenaceous and calcareous rocks, the former containing fossils related to those of the Old Red Sandstone, the latter containing fossils of a marine fauna. The Lower Devonian appears to be wanting in much of Russia, and the Middle and Upper parts of the system are generally unconformable on subjacent formations.

¹ Geikie, *Text-book of Geology*, 4th ed., Vol. II, p. 999.

Other continents. The Devonian system has a wide distribution in Siberia and China, and is known at many points in southern Asia. It occurs in North and South Africa, and in the Falkland Islands. It has great thickness (10,000 feet) in New South Wales, and has been recognized in Victoria. Rocks of this age are the oldest known formations of the North Island of New Zealand. The system has considerable development in South America, and carries an indigenous fauna akin to the Hamilton fauna of North America. So far as identified in South America, the Devonian beds are referable to the upper part of the Lower Devonian, and to the lower part of the Middle.

Climatic Conditions

Certain evidences of great diversity of climate, or of variations of climate during the period, are not at hand. The Old Red Sandstone and the Catskill formation perhaps point to aridity, but this can hardly be affirmed. In formations thought to be Devonian, evidences of glaciation have been reported from South Africa,¹ but this evidence is perhaps not conclusive.

DEVONIAN LIFE

I. The Marine Faunas

When the sea partially withdrew from the North American continent near the close of the Silurian period, the shallow-water faunas were restricted to limited bodies of water about the continental border. There appears to have been a want of free communication between these, and the life of each developed different aspects according to the conditions of each embayment. When the sea again advanced upon the land in the early Devonian from these different embayments, the advance from each carried toward the interior its own somewhat peculiar fauna. The early Devonian life therefore consisted of the expansions of these provincial faunas. They invaded the continent more or less simultaneously, but they reached the interior more or less successively. The follow-

¹ Schwarz, Jour. Geol., Vol. XIV, p. 683, and David, Q. J. G. S., Vol. XLIII, p. 195.

ing faunas have been recognized: (1) the Helderberg, (2) the Oriskany, (3) the Onondaga (Corniferous), (4) the Southern Hamilton, and (5) the Northwestern Hamilton fauna. They reached the interior in the order named. As each in turn came in contact with the previous fauna, there was a commingling and conflict of the two, resulting in the destruction of some species and the adjustment of others to one another. The final result was the development of a new, composite fauna from the survivors.

The Helderberg fauna. The Helderberg fauna seems to have developed from the late Silurian fauna in the embayment at the mouth of the St. Lawrence and on the border of the adjacent continental shelf, and perhaps also on the border of southern Europe. The fauna appears to have found a way into the Appalachian valley-trough and thence to have spread westward and northward as far as the advancing waters of the time permitted. Perhaps there was access to the interior also from embayments on the southern coast. The fauna seems never to have occupied more than the eastern part of the great interior region. The fauna of similar date in southern Europe (Hercynian) had much in common with the Helderberg fauna of America, but both differed markedly from the earlier Devonian faunas of the more northern latitudes of Europe and America.

The main features of the Helderberg fauna were a marked development of the *mollusks*, great numbers of the *molluscoids*, an erratic tendency of the *trilobites*, a scantiness of *crinoids* and *corals*, and a notable absence of *fishes*. Some of these features were doubtless due to the physical conditions of the originating tract where there was a muddy, partly calcareous bottom. So far as like conditions prevailed in the interior to which the fauna emigrated, its original characters were retained, as shown by the abundance of mollusks and molluscoids, and the fewness of corals and crinoids. The *gastropods* (*p*, Fig. 414) came into prominence, especially in the rather inferior capulid type. Certain *pelecypods* of the winged type (*aviculids*, *o*, Fig. 414) were also conspicuous. The *brachiopods* surpassed all other classes in numbers but did not develop such distinct peculiarities as the gastropods and pelecypods. The *trilobites* showed a tendency to sport, taking on strange

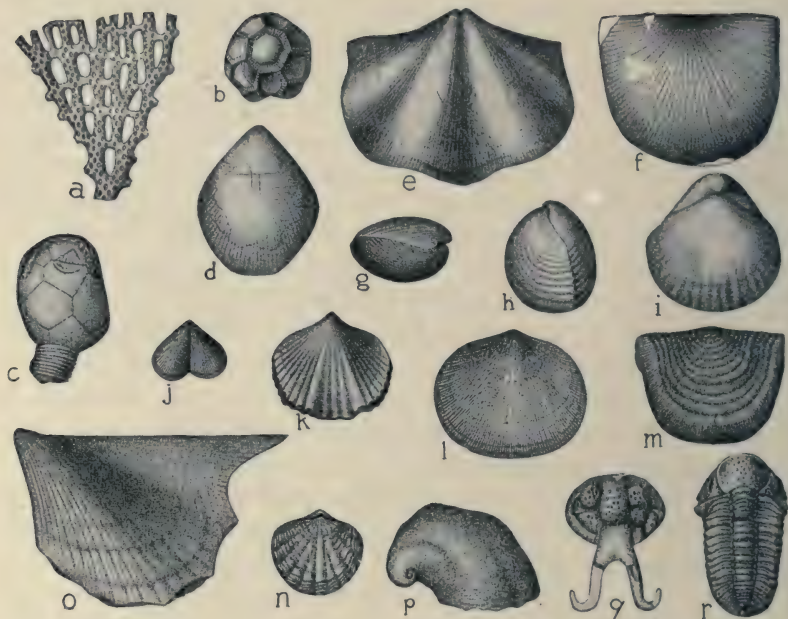


Fig. 414. — *The Helderbergian Fauna.* *a*, *Polypora lilæa* (Hall), a fenestelloid bryozoan representative of a group which was of great importance later; *b*, *Michelinia lenticularis* Hall, the earliest member of a genus of corals which became abundant in later Devonian faunas; *c*, *Lepocrinites gebhardii* Con., one of the last representatives of the cystids. *d-n*, brachiopods: *d*, *Rensselæria æquiradiata* (Con.), a representative of a genus characteristic of the Lower Devonian; *e*, *Spirifer macropleurus* (Con.), a species closely related to the Silurian species of the genus; *f*, *Strophonella punctulifera* (Con.); *g*, *Schizophoria multistriata* (Hall); *h*, *Uncinulus mutabilis* (Hall), a representative of a genus which had its greatest development in the Helderbergian fauna; *i*, *Gypidula galeata* (Dal.), one of the most characteristic species of the Lower Helderberg; *j*, *Bilobites varicus* (Con.), a type of orthid characteristic of the Silurian and Helderbergian; *k*, *Eatonia medialis* (Van.), a representative of a genus most characteristic of the Lower Devonian; *l*, *Rhipidomella oblata* (Hall); *m*, *Leptaena rhomboidalis* Wilck., a species which ranges from the Ordovician to the Mississippian; *n*, *Atrypina imbricata* (Hall), a lingering Silurian type; *o*, *Actinopteria textiles* (Hall), a winged pelecypod of a type which had great expansion in the Devonian; *p*, *Platyceras gibbosum* Hall, a capulid gastropod; *q*, *Dicranurus hamatus* (Con.), a trilobite whose closest relative occurs in Barrande's Etage G, in Bohemia; *r*, *Phacops logani* Hall, a representative of a genus of trilobites which had its greatest development in the Devonian.

forms, one of which is illustrated in Fig. 414. The *crinoids* lost the prominence they had in the Silurian and fell to an insignificant place in the fauna, probably because the physical conditions were unfavorable. For like reasons, probably, the *corals* were relatively few. The *cystoids* suffered less but were not abundant. Lower forms were present but not prominent, except that the *hydrozoan*

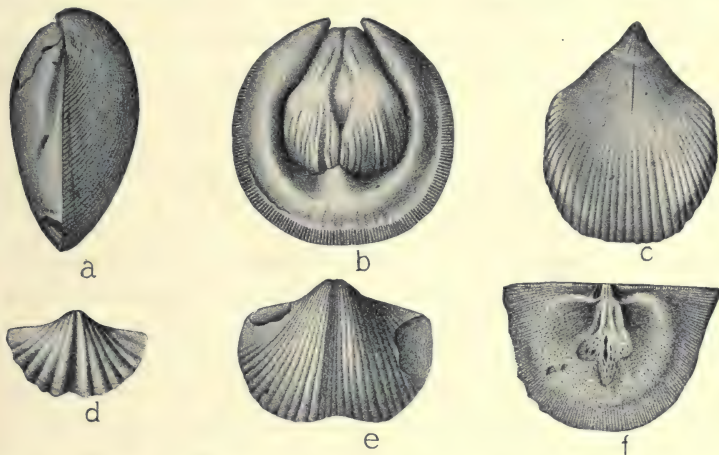


Fig. 415.— *The Oriskany Fauna. Brachiopods:* *a*, *Rensselaeria ovides* (Eaton); a representative of a genus restricted to the Helderbergian and Oriskany (see Fig. 414, *d*); *b*, *Hipparionyx proximus* Van., one of the most characteristic fossils of the arenaceous Oriskany beds; *c*, *Camarotoechia barrandei* (Hall), one of the large rhynchonelloid shells of the Oriskany; *d*, *Spirifer murchisoni* Castel, and *e*, *S. arenosus* (Con.), two of the most characteristic Oriskany species, the first occurring throughout the fauna, the second mainly in the fauna of the arenaceous beds; *f*, *Stropheodonta magnifica* Hall, a species which sometimes grew to be four or five inches across. The genus has its great expansion in the Devonian. The figures above are much smaller than the fossils, the largest shells being 4 to 5 inches across. The large size of the Oriskany brachiopod may be appreciated by comparison with Fig. 414, the brachiopods of which are reduced to the same extent as those of this Fig.

Stromatopora became common and formed thick beds. It is notable that fish remains were almost entirely absent from the Helderberg deposits, although present in the preceding and succeeding formations.

The Oriskany fauna. The Oriskany fauna followed the Helderberg into the interior apparently by a similar route. Its place of

origin is not known with certainty, but it probably had its main habitat along the Atlantic coast, for it was a sand-loving fauna and was probably distributed along the arenaceous tracts of the Devonian coasts. It was bound by many ties to the Helderberg fauna, but contained distinctive features, implying a separate origin in part. *Brachiopods* (Fig. 415) formed a leading type, some of which were notable for their great size, lengths or breadths of 2 to 4 inches being reached. Though less numerous than the brachiopods, the *mollusks* were abundant and showed some distinctive characters. The capulids were the leading *gastropods* as before, and some were exceptionally large. Some also began to bear spines, a feature which became more conspicuous later. The *pelecypods* were not very abundant, but some were phenomenally large. So many forms of unusual size among different orders imply congenial conditions of life. The cephalopods, so powerful in Silurian times, were reduced to a single species, so far as the known record shows. Trilobites were not plentiful, and corals, crinoids, cystoids, and bryozoans were rare, as might be expected from the sandy nature of the formation. Remains of fishes have not been found. On the whole, the Oriskany fauna was essentially an assemblage of well-fed mollusks and molluscoids, with but a sprinkling of other forms.

The Onondaga fauna. The Onondaga fauna was distinguished from the two preceding faunas by hosts of *marine fishes* of well-developed divergent types. From this time on fishes were abundant in the epicontinental waters of America and Europe, and doubtless ranged widely over the seas. A notable feature of the Onondaga formation consists of thin layers ("bone-beds") made up almost wholly of the plates, teeth, spines, etc., of the fishes, whose numbers must have risen into the millions. The fragmentary nature of the remains, however, makes their classification difficult, but among them were arthrodirans (joint-neck) in abundance, sharks of several orders, ganoids (crossopterygians) and doubtless other forms. The necks of the arthrodirans were so joined to their bodies as to give their heads vertical motion, a rare feature among fishes. The sharks included those which had cutting and piercing teeth, as well as those which had pavement teeth adapted to crushing shell fish.

The ancient ganoids usually had cartilaginous skeletons and bony scales, while the modern teleosts have bony skeletons and membranous scales. The fishes of the time seem to have been more fully clothed with spines and defensive armor than those of recent times. Compared with the existing species, they were doubtless heavy, clumsy, and sluggish. From the degree of development already attained, it may be inferred that the ancestors of these fishes had been living for a long time in the originating tract, probably somewhere in the north, for, as noted, they do not appear in the Helderberg and Oriskany faunas of the southeast. It is not improbable that fish were inhabitants of the northern seas from Silurian times onward. Some of the American species of arthrodians and sharks have been found in Spitzbergen, and others in Germany.

Another significant feature of the Onondaga fauna was the profusion of *corals*. From the rapids of the Ohio at Louisville, more than 200 species have been collected, embracing both the simple cup form (*a*, Fig. 416) and the compound type. Some of the cup corals attained a length of 18 inches and a diameter of 3 inches, but the range in size was great, small and large forms intermingling. The reef-building habit attained greater development than in the Silurian times, the reef at the rapids of the Ohio being the most famous example. In view of the abundance of the corals, it is rather singular that the *crinoids* were rather few, since both forms usually find clear, warm waters congenial. The crinoids, however, do not appear to have lost their vitality, for they appeared in abundance later. Very likely they may have been depressed by some hostile organic influence. *Cystoids* have not been found. They were far down their declining curve toward extinction. *Blas-toids* were present (*b*, Fig. 416) but other echinoderms have not been found. *Brachiopods* formed an important part of the fauna, many of them being large and giving evidence of congenial conditions. In contrast with the Helderberg and Oriskany faunas, *cephalopods* were abundant. It will be remembered that in the primitive types of the cephalopods, the septa of the shells were plane or symmetrically curved, and that their juncture with the outer shell was a simple curve. In the Onondaga epoch one form had septa which

were abruptly bent, and suture lines which were lobed (*i*, *Goniatites*, Fig. 416). This was the first notable step in a remarkable series of crumplings of the septa which developed later. *Gastropods*, similar to those of the earlier Devonian faunas, were present and the spines

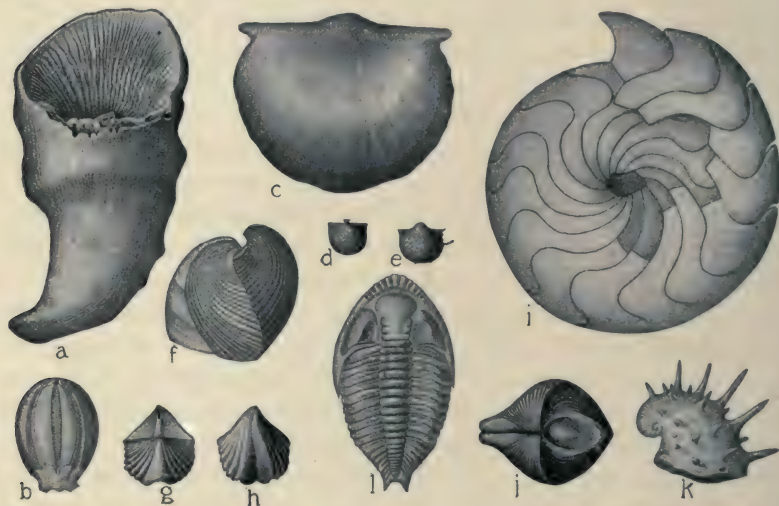


Fig. 416.—*Onondagan Fossils*: *a*, *Zaphrentis ponderosa* Hall, a medium-sized, simple horn coral; *b*, *Nucleocrinus verneuili* (Troost), a blastoid abundant in one layer of the Onondagan limestone in the Ohio valley; *c-h*, brachiopods: *c*, *Stropheodonta concava* Hall; *d* and *e*, *Productella spinulicosta* Hall, an early representative of a genus which became abundant in the Upper Devonian, and gave rise to the typical *productus* of the Mississippian and Pennsylvanian faunas; *f*, *Spirifer acuminatus* (Con.), a characteristic Onondagan brachiopod; *g* and *h*, *Crytina hamiltonensis* Hall, two views of a species having a wide geographic distribution and a great geologic range in the Middle and Upper Devonian; *i*, *Tornoceras mithrax* (Hall), the first goniatite in America. The goniatites are distinguished from earlier cephalopods by their lobed sutures; *j*, *Conocardium trigonale* Hall, a dorsal view of a common Onondagan pelecypod; *k*, *Platyceras dumosum* Con., a capulid gastropod with large hollow spines; *l*, *Odontocephalus ægeria* (Hall), a trilobite showing ornamentation of the border of the head and tail.

of the shells had now become pronounced among the capulids, which perhaps signifies the necessity of defense against the abundant fishes and cephalopods. *Pelecypods* were also abundant, and many of them resembled those of the Helderberg and Oriskany faunas,

from which they were doubtless descended. *Trilobites* were present in more than half a hundred species, a notable increase over the number known in the same region in the preceding epoch. The high degree of ornamentation of many of the species was a conspicuous feature. Barnacles were present, as were also annelids, sponges, hydrozoans, bryozoans, and protozoans. All of these played inconspicuous parts, though in the economy of the whole they were doubtless not unimportant.

Reviewing these features, it may be said that certain of the forms were clearly the descendants of species that came into the interior sea from the eastward as members of the Helderberg and Oriskany faunas. At the same time, there were prominent elements of the fauna, particularly the host of fish, cephalopods, and corals, which seem, with equal clearness, to have come in from some other source. A very characteristic development of these latter elements is found along the Straits of Mackinac, while to the north, in the James Bay basin, less than 300 miles away, there was a fauna of similar aspect. This suggests a connection between these localities, along which these new elements of the fauna migrated; but there is no positive evidence of a former connection across the intervening tract. It is known, however, that the formation has been, in part at least, removed from this tract. On the whole the striking features of the fauna seem to be most readily explained by supposing that there was a generating tract to the north,¹ either on the American or European continent, and that from this source migration into the interior sea took place as the waters from both the north and the south extended themselves upon the face of the continent. As the result of the invasion, some part of the Oriskany fauna, which already occupied the interior sea, was driven out or destroyed, while the rest intermingled with the northern invaders. In further support of this conclusion, there is no evidence that any of the Onondaga species supposed to have come from the north found their way into South America, while, on the other hand, certain of the Oriskany species lived there and certain of the Hamilton species, which appear to have come in from the south a little later, also lived in South America.

¹ This conclusion is not universally accepted.

The Southern Hamilton fauna. At the beginning of the Hamilton epoch, there was a great influx of muddy material into the eastern part of the interior sea, while the formation of limestone continued as before in the western part. This appears to have been the result of crustal warping, which affected stream-erosion and inwash on the east, and closed the straits through which the Helderberg and Oriskany faunas had entered, while in the southwest, downward warping made a more open connection between the interior sea and the ocean in that direction. At any rate, it appears that a fauna whose relatives lived in South America, entered the interior sea, and, joining the resident Onondaga fauna, led to the evolution of the Southern Hamilton fauna. In the

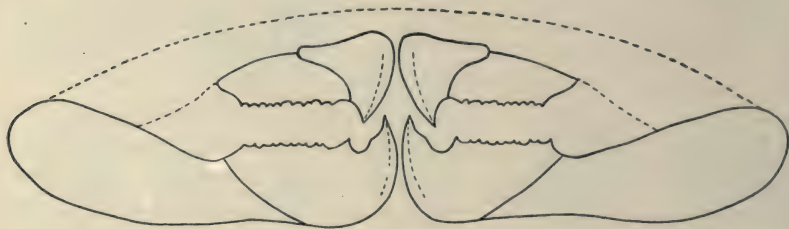


Fig. 417.—Diagrammatic front view of the dentition of *Dinichthys herzeri*, Huron Shales, Delaware, O. (After Newberry.)

earlier stages, the resident clear-water fauna was thus forced to contend with the increasing turbidity of water on the one hand, and with the southern immigrants on the other. This led to a change of the resident fauna to fit the new conditions, and to the absorption and accommodation of the invaders. It was not so radical a transformation as that which attended the previous invasion from the north that gave rise to the Onondaga fauna, because then the invaders were the master type.

The fishes played a conspicuous part in the new fauna.¹ The *arthrodirans* reached their climax, and some of the species were among the largest and most formidable fish ever known. *Dinichthys* (Fig. 417) had an estimated length of 20 feet, and was armed with formidable mandibles 2 feet in length which, in-lieu of teeth,

¹ Eastman, Mem. N. Y. State Mus., Vol. X.

had cutting edges that closed shears-like, much like the mandibles of a turtle. The front part of the body was encased in heavy plates. Related types of less formidable aspect were also known. The *sharks* left abundant relics in the form of teeth and fin spines, some of the latter reaching a foot in length. In both classes, the devices of warfare make up nearly the whole record, and this doubtless correctly implies the state of affairs of the vertebrate kingdom.

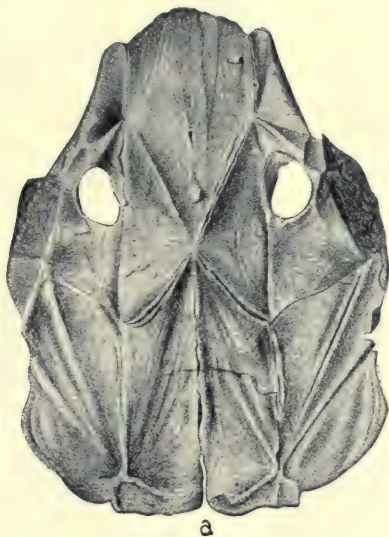


Fig. 418.—*Macropetaliethys sullivanti* Newb., plates on the head of a characteristic Onondagan fish.

Corals were affected adversely by the increased turbidity of the waters, but continued in diminished importance, especially in the western part of the interior. *Crinoids* were abundant locally. for certain beds of limestone are composed largely of their remains. Most of the genera were the same as those of the Onondaga epoch, but there were some new ones foreshadowing the remarkable development of the crinoids in the Mississippian period. The climax of the *brachiopods* was somewhere about this time. In-

articulate brachiopods still persisted as a minor factor, while the more highly differentiated forms attained wide diversity and high rank. The *spirifers* reached the greatest extension of their hinge-line (*j*, Fig. 419) a feature peculiarly characteristic of the Hamilton

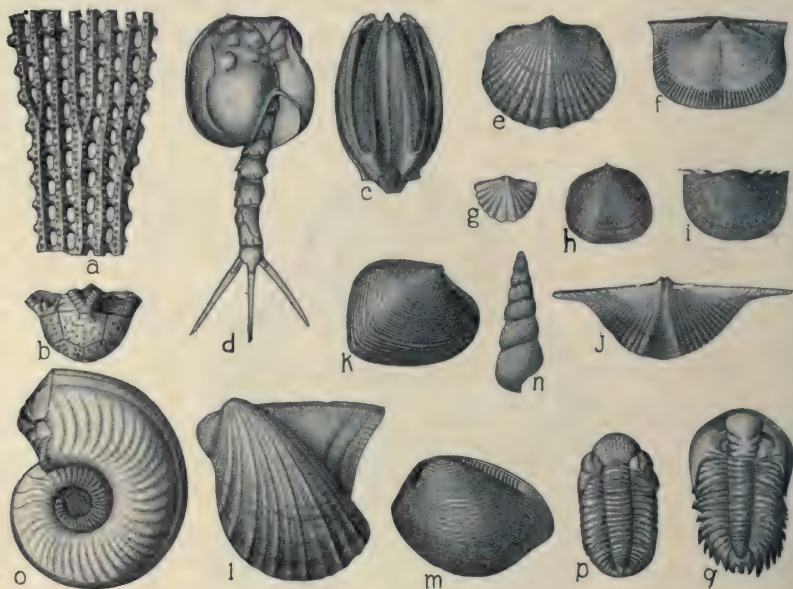


Fig. 419.—*Representative Hamilton Fossils*; *a*, *Fenestella emaciata* Hall, a type of bryozoan common in the Middle Devonian; *b*, *Arthracantha punctobrachiata* Williams, one of a genus of crinoids restricted to the Middle and Upper Devonian; *c*, *Eleutheroocrinus casedayi* S. and Y., a peculiar, irregular blastoid; during life it probably rested upon one side on the sea bottom. *d*, *Echinocaris punctata* (Hall), a crustacean more highly organized than the trilobites. *e-j*, brachiopods: *e*, *Tropidoleptus carinatus* (Con.); *f* and *i*, *Chonetes coronatus* (Con.); *g*, *Vitulina pustulosa* Hall; *h*, *Rhipidomella vanuxemi* Hall, a representative of the orthids, which had great development in the Devonian; *j*, *Spirifer pennatus* (Atw.), one of the long-hinge-lined spirifers most conspicuous in the Middle and Upper Devonian; *k*, *l*, and *m*, pelecypods: *k*, *Cypricardella bellistriatus* (Con.); *l*, *Pterinea flabella* (Con.); *m*, *Palæoneile constricta* (Con.); three pelecypods common in the Hamilton. *n*, *Loxonema hamiltoniæ* Hall, a gastropod common in this epoch; *o*, *Goniatites vanuxemi* (Hall), a characteristic cephalopod of this fauna; *p*, *Phacops rana* (Greene), the most common trilobite of the Hamilton, and representative of a genus which has its greatest expansion in the Devonian; *q*, *Cryphæus boothi* Greene, one of the last of the dalmanites. Note the serrated margin of the tail.

epoch, and subordinately of the Devonian generally. Some specimens had the breadth along the hinge-line four or five times as great as the length of their shells. The *Orthis* family, once so prominent, had fallen to a lower place, while the *productids* made notable advances toward their great expansion in the Carboniferous period (Fig. 419). Some of the brachiopod species were closely related to species that lived in South America just before their appearance in the North American fauna, which supports the view that they were immigrants from the south. The muddy bottoms favored the *mollusks*. The *goniatites* increased in numbers and size (Fig. 419). Some of the species began to exhibit node-like ornamental expansions of the shell which became a conspicuous feature later. Some of the primitive straight cephalopods still persisted. The *pelecypods* especially were favored by the muddy bottoms and the number of recognized species approaches 200. A part of these were derived from Onondagan predecessors, while others were peculiarly Hamilton types, being immigrants or forms whose parentage is unknown. The *gastropods* were inferior to the *pelecypods* in number. Their genera were mostly Onondagan, though the species were largely new. The Hamilton *trilobites* were inferior to the Onondagan in numbers and ornamentation. Other crustaceans showed some increase of representation. At this time appeared the first known *barnacles* of the northern sessile type. In losing its pedicel and in fixing itself immovably on other objects it became degenerate, but it found a lowly place to which it has hung with wonderful persistence, not unlike the debased human class which it has come to typify.

The Northwestern Hamilton fauna. While the preceding fauna was developing in the eastern interior sea, another fauna was evolving on somewhat different lines in a sea which, advancing from the northwest, appears to have overspread a large tract of the northwestern interior. This sea embraced a portion of the Mackenzie basin and extended southward through Manitoba to Iowa and Missouri. For a time this northwest sea was not in communication with the sea in which the Southern Hamilton fauna lived (Fig. 409), but it finally crossed the intervening barrier and its fauna overran the territory already occupied by the Southern

Hamilton fauna (Fig. 410). The northwestern fauna was so closely allied to the Devonian fauna of eastern and central Europe that free intercommunication between the two regions at the north is inferred. The sea arm that reached down into the American interior was perhaps no more than an eastern extension of the Eurasian Middle Devonian province.¹ The southward extension of this great arm of the sea took place late in the Devonian period, for the strata bearing its peculiar life lie on pre-Devonian formations in Missouri, Iowa, and Minnesota, and overlie the Hamilton in the more eastern region.

Evidence of geographic connections. In Europe there is a horizon so well marked by one species of brachiopod (*Hypothyris* (*Rhynchonella*) *cuboides*) that it is known as the "cuboides zone."² This species also occurs in eastern Asia (China), in northwestern America (Mackenzie valley), in western America (Great Basin), and in the American interior as far east as New York (Tully limestone). Several other species have a similar range. None of them had close allies or progenitors in the Southern Hamilton. On the other hand, allied forms have been found in England, Belgium, France, Germany, Russia, Persia, and China. This seems to make it clear that the derivation was from that quarter. A second wave of European immigration is suggested by the fauna of the Portage beds of western New York, characterized by an abundance of goniatites.³ A still later wave brought in some of the most characteristic members of the Chemung fauna. The corals of the Northwestern Hamilton fauna were of the Onondaga type, which seems to indicate that at an earlier stage, the Onondaga fauna and the ancestors of the Northwestern Hamilton fauna were in communication, as might well have happened from the northern habitat of both.

The later Devonian (Chemung) fauna. The commingling and conflict which attended the invasion of the eastern and southern

¹ Weller, Jour. Geol., Vol. VI, p. 306.

² Williams, The Cuboides Zone and its Fauna, Bull. G. S. A., Vol. I, p. 481, 1890.

³ Clarke, J. M., 16th Ann. Rept. N. Y. State Geol. and Mem. N. Y. State Mus., Vol. VI.

interior sea by the European and Eurasian faunas may be regarded as the controlling event in the evolution of the Upper Devonian fauna. As in the case of the Onondaga invasion, the northern fauna proved the more virile, and gave character to the composite fauna that later arose from the extinction of the weaker species and the adaptation of the survivors to one another. There were three dominant factors in this development, (1) the resident Southern Hamilton species, (2) the invading European and Eurasian species, and (3) the shallow and rather turbid waters in which these species met and merged. The last of these factors expressed itself in a notable rarity of *corals*. Though the turbid waters would hardly have been congenial to the *crinoids*, they were represented, as well as a few other echinoderms. The *brachiopods* best express the outcome of the commingling of resident and immigrant species. As in the case of the total fauna, there was an indigenous set of species developed from the preceding residents, and an exotic set derived from the emigrants and bearing North-European characters. The foreign group was more conspicuous than the native. Among the *mollusks*, however, the case was the reverse, and the majority seem to have been descendants of the resident bivalves. The record of the *fishes* was a decline in the arthrodirans, an increase in the sharks, and a continuation of the ganoids without great change. The record of the minor forms was not especially characteristic.

The Devonian fauna in the Great Basin area. In the region which constitutes the Great Basin of the west, a large area seems to have been occupied continuously by the sea from about the beginning of the Middle Devonian time to the later portion of the Carboniferous period. It seems to have been measurably free from both the physical and the biological changes which gave such diversity to the eastern provinces. The fauna had a slow, continuous evolution, favored, from time to time, it would appear, by accessions from the north and perhaps from other sources as well. None of the distinctive South American forms appeared in it, nor any of the peculiar Helderberg or Oriskany forms. It is inferred, therefore, that it was disconnected from the eastern and southern interior throughout the whole Devonian period. On the other hand, a notable number of species were common to it and to the

northwestern province, as also to the interior province after the latter had been invaded by the Onondagan and Northwestern Hamilton faunas. While its fauna is not yet known well enough to permit final conclusions, it bids fair to offer a fine example of a steady, uninterrupted development of a provincial fauna.

II. *The Life of the Land Waters*

Principle of interpretation. For geological purposes, all fishes that lived in streams and lakes, and those of the freshened waters of the estuaries, bays, and inlets on the land border, may be classed as fishes of the land waters. But there is difficulty in some cases in determining which sedimentary formations were made on the land or in land waters, for terrestrial, marine, fluvial and estuarine types of life may be mingled by the carriage of land forms to the sea. Fossils do not always tell us, therefore, whether a formation was made in the sea or on land. The deposits forming to-day in the great valley of California embrace pluvial, fluvial, lacustrine, and marine deposits. At a geologically distant day, only small parts of this aggregate would probably be fossiliferous, and the evidence from various points might be quite opposed. This appears to be very much the state of things recorded in the "Old Red Sandstone," in the Catskill formation, and elsewhere. As all these deposits were laid down in more or less local basins, probably, their exact correlation is impossible, and their faunas may be considered together. The general faunal conception is that in the Appalachian tract and in the Canadian provinces lying to the northeast of it, as well as in Great Britain and Russia, there were many lodgment basins that were progressively filled by land-wash and fresh-water sediments, and that these basins were the home of a fresh- or brackish-water fauna, of which ostracoderms, fishes, and crustaceans were the most conspicuous members. Perhaps the geological record presents no more suggestive combination of ancient life. The type of the fauna was foreshadowed by the eurypterids and fishes, or fish-like forms of the late Silurian; but the record of that time is more imperfect than that of the late Devonian.

The ostracoderms. The center of interest in this fauna is found in the *ostracoderms* (Figs. 420 and 421), which were first

interpreted as placoderm fishes, later as jawless fishes, and now as a distinct class between the arthropods and the vertebrates.¹ Their chief interest lies in their suggestion that the vertebrates sprang from the arthropods. The ostracoderms bear external

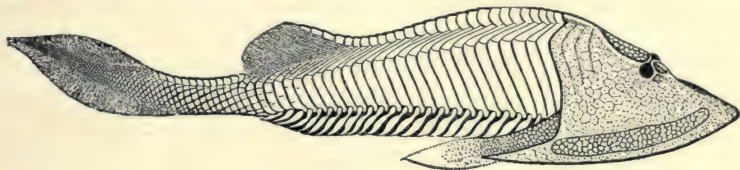


Fig. 420.— Restoration of *Cephalaspis*, seen from the side. (After Patten.)

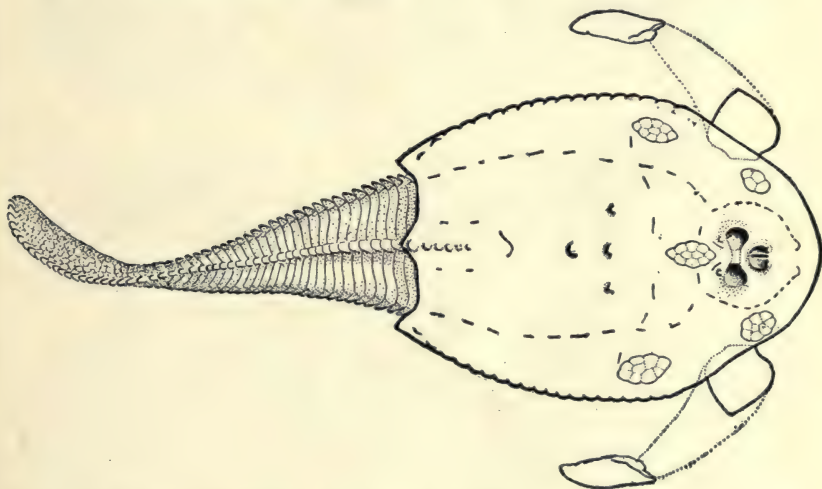


Fig. 421.— Reconstruction of the head and trunk of *Tremataspis*, seen from above. Natural size. (After Patten.)

resemblances, in the head and trunk, to trilobites and king-crabs, while some of them have caudal fins and fish-like bodies. Because of their fish-like features and the presence of bone cells in the dermal

¹ W. Patten, On the Origin of Vertebrates, with special reference to the structure of the Ostracoderms. International Zoöl. Cong., Berlin, 1901. On the Appendages of *Tremataspis*, Am. Nat., XXXVII, 1903, p. 223. On the Structure of the *Pteraspidae* and *Cephalaspidae*, Am. Nat., XXXVII, 1903, p. 827. New Facts concerning *Bothriolepis*, Biol. Bull. No. 2, 1904, p. 113.

armor of some of them, and because of their intimate association with true fishes, they were formerly classed as fishes. But no vertebræ (or notochord) has been found, or appendages or jaws of the vertebrate type. On the contrary, each jaw consists of two separate parts which act upon one another, not vertically, in vertebrate fashion, but *laterally*, as in arthropods. This is especially true of the upper jaw. The ostracoderms probably formed the climax and almost the end of their own strange race, for they practically disappeared with this period. Their disappearance is not surprising in view of the development of powerful fishes, for the ostracoderms were obviously not a masterful race. Besides being small, they were clumsy, their locomotive organs lacked flexibility and efficiency, and their mouth-parts were weak. They probably



Fig. 422.—*Palæospondylus gunni*, restored by Traquair; from the Old Red Sandstone, Caithness, Scotland. (After Dean.)

plowed the soft bottoms of the sluggish waters, half buried in the mud, above which little beside their peculiarly placed eyes and the backs of the plated bucklers were habitually exposed. While the ostracoderms are sometimes reported as occurring in beds with marine fossils, there is little evidence that they were dwellers in the open sea.

In view of the arthropodan relations of the ostracoderms, it is suggestive that in the Devonian time, as in the closing stages of the Salina, there were gigantic eurypterids associated intimately with the ostracoderms and the fishes. The largest of the arthropods (*Pterygotus*) reached the extraordinary length of two meters. It has already been suggested that this association of arthropods and vertebrates ran back to their origin, and it may be added that it has run on until the present day, for the fish and the arthropods (crayfish and smaller crustaceans) dominate the fresh waters.

Another strange class of organisms related to the fishes, but not true fish, was represented by the singular little lamprey-like cyclostome *Palæospondylus* (Fig. 422), which, it has been conjectured, was really an ancestral lamprey. In any case, this animal represents the vertebrate idea in great simplicity; a slender column of vertebræ, modified at one end into a head and finned at the other for a tail, without ribs or paired fins, or any suggestion of limbs, make up the known structure.

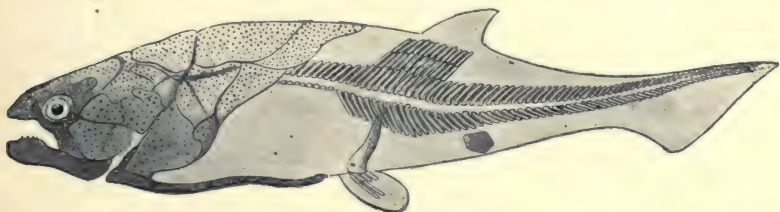


Fig. 423.—A partial restoration of *Coccosteus decipiens*; from the Old Red Sandstone of North Scotland. About $\frac{1}{4}$ natural size. (After Woodward.)

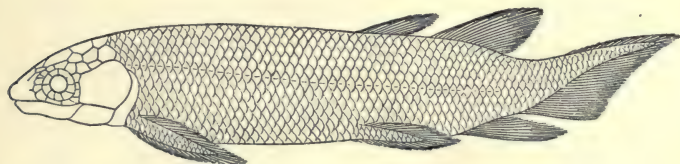


Fig. 424.—*Dipterus valenciennesi*, restoration by Traquair; from the Old Red Sandstone, North Scotland; about $\frac{1}{2}$ natural size.

The true fishes found in the supposed fresh-water deposits of the Devonian exceed in number and variety those found in the contemporaneous marine formations. Perhaps the strangest of them were the *arthrodirans* (Fig. 423), whose relations to other fishes are puzzling, but most paleontologists regard them as a specialized and rather divergent branch related to the ancestors of the lung-fishes (*Dipnoi*) which reached their climax at about this time. *Crossopterygians* (fringe-finned ganoids) were present,

and showed in their teeth and skull-bones, many resemblances to the amphibians, of which they were perhaps the ancestors. Like the lung-fishes, they appear to have been at or near the climax of their evolution at this time, though they lived on in large numbers to the Cretaceous. Sharks (*elasmobranchs*) are now chiefly marine, and (unless the Paleozoic era be excepted) have been so throughout known geological time, though a few live in fresh water, as in Lakes Nicaragua and Baikal. In the Devonian period they seem to have lived in the open sea, but their remains are also found in the Old Red Sandstone and equivalent formations, so that they probably lived in fresh and brackish waters, as well as in the ocean.

Shells believed to have belonged to fresh-water mollusks, and closely resembling living genera, have been found, in association with land plants and fishes. Little is known of the fresh-water vegetation.

III. *The Land Life*

The known land life of the Devonian period consisted of plants, snails, insects, myriapods, scorpions, and traces of amphibians; but the record of land life is very imperfect. In the early stages of its evolution, vegetation was doubtless more perishable than later; but even now plant tissues are less well fitted for fossilization than the shells and skeletons of animals. The normal fate of up-land plants is to perish where they grow, and to disappear by decay, consumption, combustion, or some other form of destruction. The chances of the prompt burial and preservation of lowland vegetation are better; but it is only when the low land is being rapidly aggraded, that the conditions for the fossilization of its vegetation are even fairly favorable. Even when preserved, it is rare that leaves, fruit, twigs, limbs, trunk, and roots are all preserved together. So true is this that in the case of ancient plants, especially if not closely analogous to modern types, it is more or less hazardous to attempt to restore the original plant by combining the dismembered parts of different individuals.

The Devonian period covers much of the early development, though probably not the actual beginning of terrestrial plant life. It saw the origin of ferns, scouring rushes, lycopods, the seed-

bearing relatives of the conifers, and probably the "seed-bearing" ferns.¹ The Devonian plants were, on the whole, but sparsely foliate, their leaves being spinoid and small. They perhaps descended from amphibious ancestors, which, in turn, were derived from some of the various types of plants which lived in the sea. If so, the expansion of leafage and the development of an aerial system of transpiration were probably evolved slowly as the plants were weaned from their aqueous habitat. The occurrence of most of the fossil remains in fresh or brackish water or lowland deposits gives a suggestion of the habitats of the flora. Of the upland vegetation nothing is known.

The early Devonian plants appear to have had a strengthened cuticle which helped to support their weight, a function which was discharged later by the woody axes developed by their descendants. It is inferred from the fossils that some of the plants were unable to stand alone, but sprawled about on the ground or clambered over other plants.

The Middle Devonian flora of Maine (Chapman sandstone) is so like a flora of Scotland, Belgium, and the Rhine provinces, as to indicate the probability of the migration of land plants between our continent and Europe, perhaps by way of a land bridge between high latitudes of America and Europe. The Portage flora of New York is found also in Bohemia. In general, the Upper Devonian flora was very similar from Pennsylvania to southern Europe, and this wide-spread flora has something in common with the Devonian flora of Australia. The Devonian fossil woods show no rings indicative of seasonal changes or long periods of drought.

The types of Devonian plants were similar to those of the next period. The dominant forms were fern-like plants, some of which were seed-bearing, and the lower gymnosperms. The forerunners of the lepidodendrons were present in the Middle Devonian, and before the close of the period the forerunners of the sigillarias appeared.² Angiosperms had not yet come into existence, so far as known.

¹ David White, *Jour. Geol.*, Vol. XVII, 1909. Many of the statements of the following paragraphs are from this article.

² For classification, see p. 944.

The forests were made up chiefly of (1) the *calamites* (*Equisetales*) the gigantic ancestors of the horsetails, (2) the *lepidodendrons*, gigantic ancestors of the club-mosses, and (3) the *cordaites*. All of these were better developed in the flora of a later period.

The record of the lower land plants is almost negative, except that, singularly enough, bacteria have been reported.¹ The identification of such simple forms in fossilized woody tissue at so ancient a period is remarkable, though the presence of bacteria is altogether probable in itself, for the record of plant life should have been more perfect than it is, had decay not been promoted by bacteria.

The general aspect of the fern-like, seed-bearing plants was very like that of existing ferns, but some families were archaic and



Fig. 425.—A, *Platephemera antiqua*, Sc., St. Johns, N. B. (After Scudder.)
B, *Xenoneura antiquorum*, Sc. From St. Johns, N. B. (After Scudder.)

peculiar. The larger number were herbaceous, but there were arboreous forms not unlike existing tree-ferns in general appearance. These plants were already so far advanced in their evolution that little is certainly known relative to their ancestral relations. They are generally thought to have been the progenitors of the Bennettitales, and through them of the cycads and of most or all other gymnosperms. In numbers, the fern-like forms appear to have surpassed all others.

Numerous wings and other fragments of insects have been found, chiefly near St. Johns, New Brunswick.² They show that

¹ Renault, Ann. Sci. Notes, Vol. II, 1896. See also Seward, Fossil Plants, 1898, pp. 133–138.

² Scudder; a list is given in Bull. No. 71, U. S. Geol. Surv., 1891. Question has been raised as to the Devonian age of these.

the insects were of archaic and synthetic types most nearly allied to modern neuropters and orthopters; but they combined characters now found in different orders. Myriapods, arachnoids, and a scorpion are reported from plant-beds in New Brunswick, and myriapods have been found elsewhere. Terrestrial mollusks are also reported from New Brunswick.

CHAPTER XX

THE MISSISSIPPIAN (EARLY CARBONIFEROUS) PERIOD

FORMATIONS AND PHYSICAL HISTORY

The time from the close of the Devonian period to the end of the Paleozoic era was formerly regarded as the *Carboniferous* period. But this interval is now commonly divided into two or three divisions, each of which is given the rank of a period. If three divisions are made (as here), the first is the *Mississippian* period, also known as the *Subcarboniferous*, or *Lower Carboniferous*. It represents a time of wide-spread submergence of the North American continent, and was brought to a close by wide-spread emergence of the area where marine sedimentation had been in progress. The second, the *Pennsylvanian* period, (also known as the *Carboniferous*, *Coal Measures*, and *Upper Carboniferous*), represents a time when the area between the Appalachian Mountains on the east and the 100th meridian on the west maintained a halting attitude, being now slightly above sea-level and now slightly below it. West of the Great Plains, submergence was rather general, as during the preceding period. The third division of the old Carboniferous period is the *Permian*, a time of notable crustal deformation, general aridity, and, during part of the period at least, low temperature.

The Mississippian was a period of widespread submergence, a submergence which began in the late Devonian; but its close was marked by the emergence of large portions of the continent. In keeping with this definition of the period, the earlier beds, deposited while the advance of the sea was in progress, are less wide-spread than those of later stages, when submergence had become more general.

The following subdivisions of the Mississippian system are recognized in the regions indicated:

- | Mississippi River States | Pennsylvania |
|--|----------------|
| 4. Chester (or Kaskaskia) series (including the Cypress sandstone below, and the Chester beds above). | 2. Mauch Chunk |
| 3. St. Louis series (including Salem limestone below and the St. Louis and Ste. Genevieve limestones above). | |
| 2. Osage or Augusta (including the Burlington limestone, Keokuk limestone, and Warsaw shale) | 1. Pocono |
| 1. Kinderhook (or Chouteau) | |

East of the Great Plains

The Kinderhook stage. In the early part of the Mississippian period, coarse sediments (sands and gravels, now a part of the *Pocono formation*) were gathering along the western border of Appalachia. At the same time, the area of Southern Michigan was a sort of bay or enclosed sea into which sediment was washed from the surrounding lands. In the central part of the Mississippi basin, the sediments of this stage (*Kinderhook*) were partly elastic and partly calcareous, and the variations were not only from place to place at the same time, but from time to time in the same place. Of these formations most are marine, but the Pocono has yielded many fossils of land and plants.

The Osage stage. In the second (*Osage* or *Augusta*) stage of the period, the sea of the interior became clearer, and the deposition of purer limestone was in progress. Submergence extended westward, probably to New Mexico on the one hand and to Montana on the other. The similarity between the fossils of the Mississippi basin at this stage, and those of the corresponding strata of Europe, is thought to indicate some available route of travel for marine species (especially crinoids) between these widely separated regions. Shallow water, and the absence of great variations of temperature are probably the only conditions necessary for such migration as the faunas of these widely separated regions imply.

The rich deposits of zinc ore (with some lead) in southwestern Missouri and eastern Kansas are chiefly in the Osage beds, though the metallic compounds were concentrated into ores at a much later time.

East of the Cincinnati arch, which was probably an island in the Osage epoch, the deposition of clastic sediments continued. Those of eastern Ohio constitute a part of the *Waverly* series. Farther east, the accumulation of the sand and gravel of the first stage (Pocono) either continued, or had been succeeded by the deposition of the mud which now constitutes the *Mauch Chunk* formation. The sediments of at least a part of this formation seem to have accumulated on land, rather than in the sea. In Maryland and elsewhere farther south, a formation of limestone (*Greenbrier*) lies between the Pocono below and the Mauch Chunk above, and the Newman limestone of other regions¹ is perhaps its equivalent.

The St. Louis stage. This stage (including the Salem or Spergen, St. Louis, and St. Genevieve limestones) marks the time of maximum Mississippian submergence, so far as the western interior is concerned (Fig. 426). Limestone deposition continued in the Mississippi basin, but the fauna which it contains is so unlike that of the Osage stage as to indicate that geographic changes of consequence to the marine life of the interior had taken place. One of these changes seems to have involved the removal of a barrier somewhere in the west, permitting the fauna of the Great Basin, heretofore shut off from the interior, to migrate eastward, and mingle with that of the Mississippi basin.

It was during this epoch that the Bedford limestone² of Indiana (*Salem* or *Spergen* formation), famous as a building stone, was deposited. Much of this limestone, long mistaken for oölite, is foraminiferal. Many of the great limestone caves in Kentucky and southern Indiana are in the beds of this epoch. In Michigan, beds containing salt (brine) and gypsum were in process of deposition, as also earlier in the period.

In the northern part of the Appalachians the Mauch Chunk shales were doubtless in process of deposition, while other names are applied to the contemporaneous deposits in the mountains

¹ See Tennessee folios.

² The name *Bedford*, as applied to their limestone, is really a trade name. As a geological term, Bedford is applied to a member of the *Waverly* series farther east.

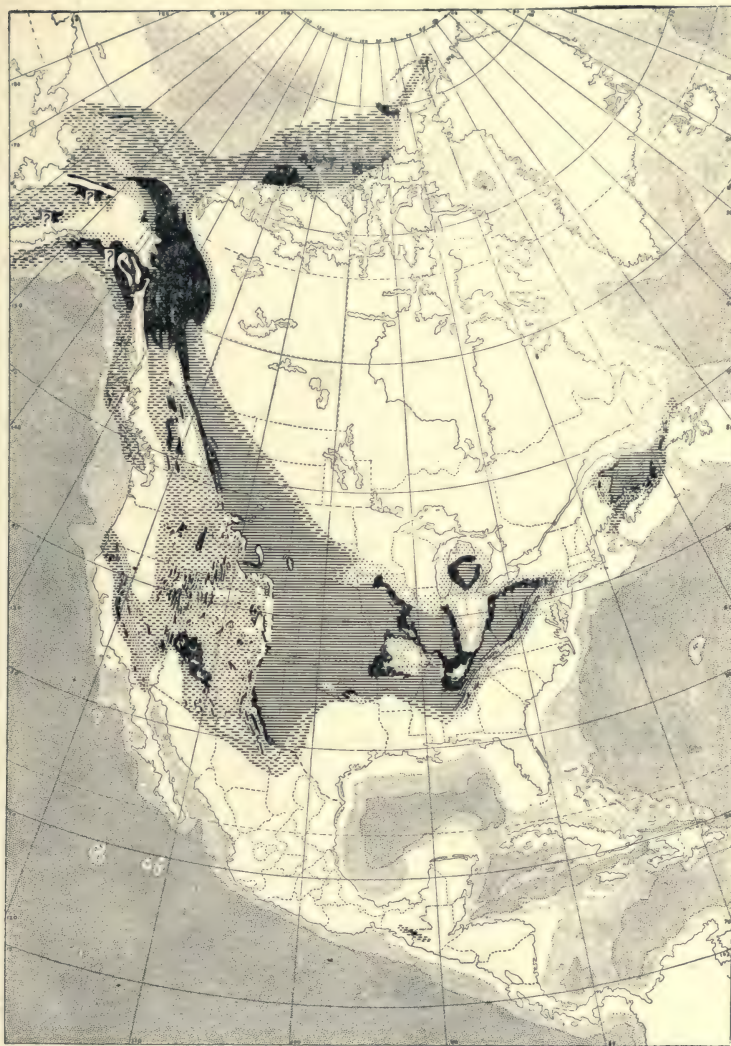


Fig. 426.— Map showing the areas, in black, where the Mississippian system appears at surface. The map also shows where the Mississippian system is thought to exist, though buried (the lined areas), and the area from which it is thought to have been removed by erosion (the dotted areas). By inference, also, the map shows the relations of land and water during the Mississippian period.

farther south.¹ Locally, deposits of this time contain both coal and iron ore.

The Chester stage. The fourth stage of the Mississippian period (Chester), according to the classification adopted for the Mississippi basin, seems to have been marked by more restricted waters and more varied sedimentation, for sandstone and shale are prominent members of this series. The deposits of this stage resemble in a general way those of the Kinderhook stage. Those were made while the sea was advancing on the land, these while it was retreating. Both are more restricted in their distribution than the beds of the intermediate epochs. In Illinois, the Chester sandstone bears oil locally.²

In summation it may be said that the Mississippian beds are predominantly clastic east of the Cincinnati arch, and predominantly calcareous west of it. In many places the limestone of the system carries great quantities of chert.

In Nova Scotia, the Mississippian system rests, locally, on Cambrian and pre-Cambrian terranes, and contains beds of red sandstone and gypsum.

In the Great Plains

In the Great Plains, the Mississippian system is known in Oklahoma and South Dakota, where deformation and erosion have brought the strata to the surface (Fig. 426). In Oklahoma there was some deformation at about the close of the period. The up-warped beds suffered erosion, and an extensive chert-conglomerate, the conditions for which were prepared by the interval of erosion, marks the first stage of Pennsylvanian deposition.

West of the Great Plains

West of the Great Plains the Lower Carboniferous is so widely distributed as to show that the present mountain region, as far west as the 117th meridian, was mostly submerged, though there

¹ The name Mauch Chunk is applied as far south as Maryland; see Jour. Geol., Vol. IX, pp. 422-424.

² Bain, Econ. Geol. Vol. III, and Bull. 2, Ill. Geol. Surv.

were perhaps numerous islands,¹ some of which occupied the position of existing mountain cores. North of the United States, also, marine conditions prevailed widely. The several stages of the period, as defined in the Mississippi basin, have not been separately recognized in the west. Much of the system in the west is limestone, though clastic formations are not wanting.² The system is exposed about many of the mountains of the west, and over considerable areas in Arizona and perhaps in New Mexico. It rests on the Ordovician in many places, and it sometimes overlaps all earlier Paleozoic systems, lying upon the Proterozoic. It attains a thickness of several thousand feet in places. In some parts of Colorado³ (Leadville) the Mississippian limestone and dolomite constitute one of the richest ore horizons of the state.

In many parts of the west the Mississippian system is unconformable beneath the Pennsylvanian, and in many places there is an unconformity in the undifferentiated Carboniferous which probably represents the division between the two systems.

Igneous activity. According to present determinations, there was great igneous activity in the west during this period. The area affected by vulcanism at this time, or soon after, extended from Alaska on the north to California on the south.⁴ West of the Gold ranges in British Columbia, the early Carboniferous is made up largely of igneous rock, with intercalated beds of clastic sediments. Dikes affect the system of Southern Illinois and adjacent parts of Kentucky, but the date of their intrusion is not known.

General Considerations

Thickness and outcrops. In keeping with the variations in the sediments, the thickness of the Mississippian system varies greatly. In Pennsylvania, there is a thickness of 1,400 feet of sandstone (Pocono), with 3,000 feet of shale (Mauch Chunk) above

¹ Emmons, S. F., Bull. Geol. Soc. Am., Vol. I, pp. 263-267.

² The Mississippian is not differentiated from the Pennsylvanian on the maps of most of the western folios of the U. S. Geol. Surv., though the two are sometimes differentiated in the text, especially in the later folios.

³ Eldridge, Anthracite-Crested Butte folio, U. S. Geol. Surv.; and Girty, Prof. Paper No. 16, pp. 162, 163, and 217.

⁴ Dawson, Can. Geol. Surv., 1886, p. 85.

it; but so rapidly do the formations thin westward, that in the western part of the same state the equivalent formations have a thickness of only 300 to 600 feet. In the region of the Mississippi, where the system is chiefly limestone, it reaches a maximum thickness of about 1,500 feet, being thinner to the north and thicker to the south. In Oklahoma, the thickness is about 1,800 feet, in the Black Hills, 275 to 525 feet, in Colorado (Crested Butte region) 400-525 feet, and in northern Arizona (Grand Canyon of the Colorado), 1,800 feet.

The distribution of the uncovered portions of the Mississippian beds in the eastern part of the continent is shown in Fig. 426. The beds themselves are of course much more extensive than their outcrops, being extensively concealed by younger beds. Like all preceding systems, the Mississippian doubtless has wide distribution beneath the sea, where it is probably thin.

Close of the period. At the close of the period, the eastern interior sea was contracted to very narrow limits if not completely obliterated. Great changes took place in the western half of the continent too, but they are less fully determined. Evidence of their existence is found in the wide-spread unconformity above the Mississippian. In some parts of the west, however, so far as now known, marine conditions prevailed uninterruptedly from the early Mississippian period to the later part of the Pennsylvanian.

Reasons for regarding the Mississippian a distinct system. The withdrawal of the sea from a large part of the eastern interior at the close of the Mississippian period exposed the newly deposited sediments to erosion. The exposure was long and the erosion considerable. At the opening of the Pennsylvanian period, as will be seen in the sequel, a large part of this area was again the site of deposition, and the new system rests unconformably on the Mississippian over wide areas, from Pennsylvania and Tennessee on the east, to Utah and Montana on the west (Fig. 426).

The wide-spread emergence, erosion, and subsequent submergence recorded by the unconformity between the Mississippian and the Pennsylvanian systems is just the sort of change which is held to separate periods, not epochs. Nowhere else in the whole course of the Paleozoic era are so great physical changes embraced

within the limits of one period. It is for this reason primarily that the Mississippian should be separated from the Pennsylvanian as a distinct system. These physical changes were accompanied by great changes in life, as will be seen.

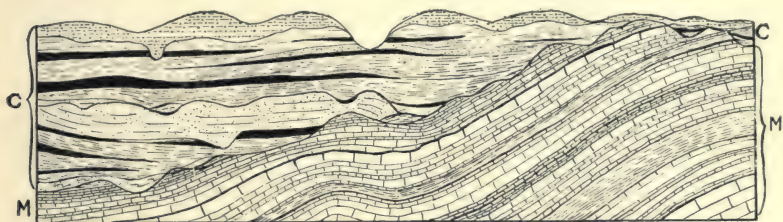


Fig. 427.—Composite diagrammatic section, showing the unconformity between the Mississippian and Pennsylvanian systems in Iowa. (Keyes, Ia. Geol. Surv.)

The Lower Carboniferous of Other Continents¹

Europe. The post-Devonian Paleozoic systems of Europe resemble the corresponding systems of North America in some ways, and are in contrast with them in others. The formations in eastern and western Europe, as in eastern and western America, are notably unlike. In western Europe, two great series, or systems, are included under the Carboniferous, namely, (1) the Lower Carboniferous, chiefly of marine origin, and (2) the Coal Measures or Carboniferous proper, deposited partly in lagoons, marshes, and lakes, and partly in the sea. These two systems correspond, in a general way, to the Mississippian and Pennsylvanian, respectively, of eastern North America.

In southern Europe the Upper and Lower Carboniferous formations are like the Mississippian and Pennsylvanian of western North America, in that they are chiefly marine. In eastern Europe the Lower Carboniferous is partly marine, and partly non-marine and coal-bearing, while the Upper Carboniferous is largely marine.

Though the rocks of the Lower Carboniferous series rest con-

¹ The term Lower Carboniferous is here used, instead of Mississippian, because it is the term in common use in Europe.

formably on the Devonian in many parts of Europe, they nevertheless record considerable geographic changes, for the early Carboniferous formations of western Europe are of marine origin, while much of the underlying Devonian (the Old Red Sandstone) is not. The distribution of the two systems and the character of their formations, indicate a somewhat wide-spread, even if slight, submergence at the opening of the early Carboniferous period. This is in keeping with the course of events in North America.

The Lower Carboniferous system of western Europe, like that of North America, is largely of limestone, sometimes known as the *Carboniferous Limestone*. In Great Britain, the system early received the name of "mountain limestone," and this name has been applied frequently in North America. East of the Rhine the Lower Carboniferous limestone is replaced by shale, sandstone, and even conglomerate, collectively known as the *Culm*. This phase of the system contains coal in some places.

In eastern Europe, the system contains much coal. The coal-field of Moscow covers 13,000 square miles, but the beds of coal are mostly thin and poor. The coal-field of Donetz covers 11,000 square miles, and contains 44 workable beds (some of them Upper Carboniferous) which have an aggregate thickness of 114 feet. Workable coal beds also occur in the upturned Lower Carboniferous strata on the flanks of the Urals.

The Lower Carboniferous of some parts of Great Britain and western Europe contains much volcanic rock. Some of the eruptions were probably submarine, and some subaërial in origin.

Thickness. The thickness of the European Lower Carboniferous is very great, considering the fact that it is so largely of limestone. In England and Ireland, the limestone attains thicknesses ranging up to 2,000 feet, and perhaps even to 2,500 feet. In the northern part of England and in Scotland, where the beds are clastic, they have a thickness which, at the maximum, is much greater. In Belgium, also, the limestone is very thick, bespeaking the great duration of the period. At the rate at which limestone is supposed to accumulate, 2,500 feet of limestone would call for at least some hundreds of thousands of years.

The close of the early Carboniferous period was marked, in

Europe, by wide-spread crustal disturbances. It was at this time that a great system of mountains, sometimes called the *Paleozoic Alps*, began its development. These mountains crossed central Europe from east to west. Their remnants are seen in the Vosges, Black Forest, Harz, Sudetes, etc., mountains of the present time.



Fig. 428.— Map showing the relations of land and water in Europe in the early Carboniferous period. The shaded parts represent areas of marine deposition. (After DeLapparent.)

The development of the Ural Mountains appears to have begun at the same time. Geographic changes which were not deformative were also in progress, shifting somewhat the areas of sedimentation. In Europe as in America, therefore, there is a notable break between the Lower and Upper Carboniferous, as shown by unconformities at many points. The distinctness of the two systems is further emphasized by their unlike distribution, and by the physical unlikeness of their formations.

Other continents. In other continents, where geological work is less advanced, the Lower and Upper Carboniferous have not always been carefully separated, but the system is known in all of them. In *Australia* and *New Zealand*, the Lower Carboniferous is much disturbed and metamorphosed, and associated with more or less igneous rock. In Western Australia, as in some parts of North America, gypsum and salt are found in the system.

Climate and Duration

Most of the data at hand indicate the absence of great diversity of climate during the Mississippian (Lower Carboniferous) period, and suggest at the same time that it was genial. The salt and gypsum of the Mississippian series in Montana, Michigan, Nova Scotia, and western Australia, suggest aridity, but it is not now clear that this aridity was general. Certain conglomerate formations (the Culm) of western Europe have been thought to suggest glaciation, but the evidence does not seem to warrant this conclusion. Recently, phenomena which have been interpreted to imply floating ice, have been found in Oklahoma.¹

The period was probably somewhat longer than most of the Paleozoic periods which had preceded it.

THE LIFE OF THE MISSISSIPPIAN (SUBCARBONIFEROUS)

1. *The Marine Faunas*

Just as there was no great stratigraphic break between the Devonian and Mississippian systems in the American continent, so there was no radical break in the succession of life. It will be recalled that the life history of the Devonian in North America included a series of great invasions from different quarters, and that the invaders and the invaded mingled with one another until at the close there was an approach to a single continental fauna. The life of the Great Basin, however, was still partly isolated, and there were dependencies of the main fauna that still retained provincial features.

¹ Taff. Geol. Soc. Am. Dec. 1908.

The Kinderhook fauna. The Kinderhook fauna of the great Mississippian sea varied from region to region, apparently in response to different physical conditions. But few of its features need be noted here.

In this fauna are found the beginnings of the great deployment of the *crinoids*, which reached its climax later in the period, but other forms of echinoderms were not abundant. The *brachiopods* were transitional between those of Devonian and Later Mississippian types. Among them, the genus *Productus* was conspicuous (Fig. 429). Not a few Devonian species may be named as the probable direct ancestors of Kinderhook species, while some Devonian species still lived. *Mollusks* were prominent, the *pelecypods* (*i, j*, Fig. 429) alone having a larger number of species than the echinoderms or the brachiopods. Among them are species indistinguishable from those of the Waverly fauna that lived east of the Cincinnati island. The *gastropods* were less abundant, and among them the capulids, conspicuous among the gastropods of the Devonian, were common. The chief representatives of the *cephalopods* were the goniatites and although not abundant, they show a notable advance over any of their known ancestors, in the more highly complicated lobing of the suture. *Trilobites* were few and small. Their high stage of ornamentation had passed, and the day of their disappearance was drawing near. Among *corals* cup-shaped forms were most common. Fishes, especially sharks, were abundant.

The Osage fauna. The physical conditions of the Osage epoch present the key to the character of its fauna. Its extended shallow sea, relatively free from silt, afforded a favorable field for the evolution of the varied assemblage of forms that had come together in the preceding epochs under less favorable conditions. There is evidence also of rather free migratory communication with the Eurasian continent, since many identical and allied species were common to America and Europe.

No single group so well characterizes the Osage fauna and expresses its dependence of physical conditions as the *crinoids*, whose abundance and diversity were climacteric (Fig. 430). The rapid decline after this epoch is one of the most remarkable incidents in the life history of the invertebrates. In the day of their glory,

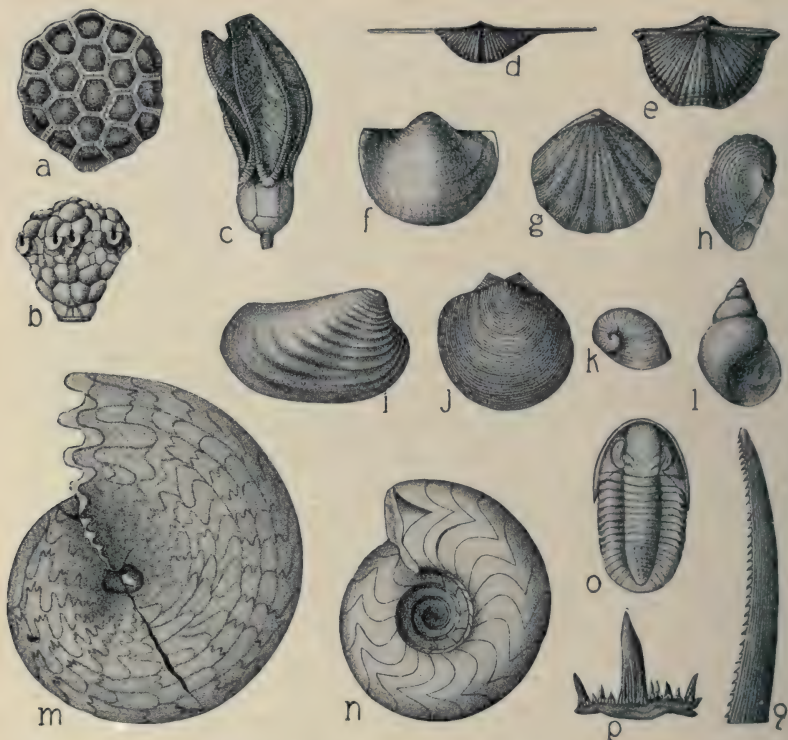


Fig. 429.—Kinderhook Fossils: *a*, *Leptopora placenta* (White), a compound coral; *b*, *Actinocrinus senectus* M. and G., a distinctively Mississippian crinoid; *c*, *Dichocrinus inornatus* W. and Sp., one of the earliest crinoids with only two basal plates. *d-h*, brachiopods: *d*, *Spirifer buplicatus* Hall, a species retaining an elongate hinge line characteristic of the Devonian; *e*, *Spirifer marionensis* Shum.; *f*, *Productella pyxidata* Hall, of a genus which had its greatest development in the late Devonian; *g*, *Paraphorynchus striatocostatus* (M. and W.), characteristic of Lower Kinderhook horizons of Iowa, Missouri, and Illinois; *h*, *Productus arcuatus* Hall, a genus developed from *Productella*, and characteristic of the Mississippian and later Paleozoic periods; *i*, *Grammysia hannibalensis* (Shum.), a pelecypod; *j*, *Pernopecten cooperensis* (Shum.), a pelecypod characteristic of certain of the higher Kinderhook horizons; *k*, *Platystoma broadheadi* S. A. M., a capulid gastropod; *l*, *Macrocheilus blairi* (M. and G.); *m*, *Prodromites gorbyi* (S. A. M.), a widely distributed cephalopod and the earliest form showing secondary lobing of the sutures; *n*, *Muensteroceras oweni* (Hall), abundant in the famous Kinderhook goniatite bed at Rockford, Ind.; *o*, *Præetus ellipticus* M. and W. Trilobites were few in the Kinderhook, and this one illustrates their characteristic lack of ornamentation; *p*, tooth of *Cladodus springeri* St. J and W., a shark; *q*, a spine of *Acondylacanthus gracilis* St. J. and W.

the crinoids were most prolific, as indicated by the fact that a single genus (*Batocrinus*,) had more than a hundred species. The ornamentation of the crinoids at this time was notable, and as in the case of the trilobites, preceded the decline of the group. The repetition of this singular phenomenon at different times, and in quite different groups of organisms, is worthy of notice, though its

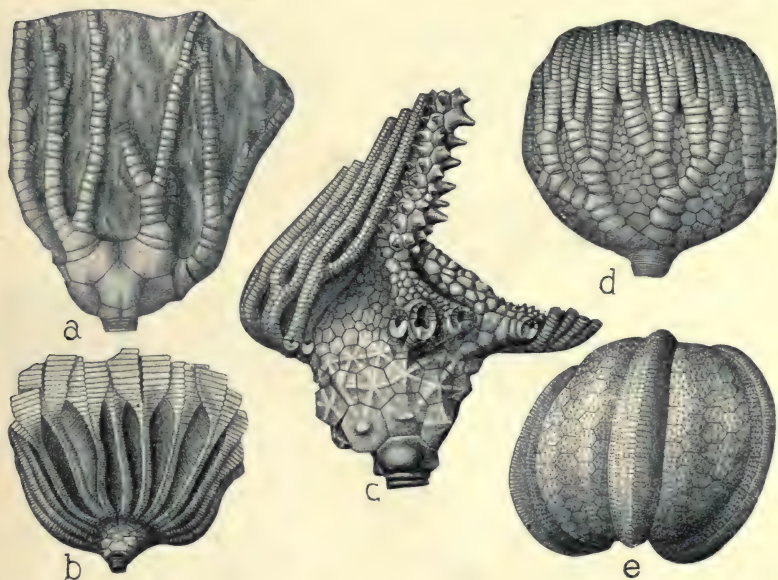


Fig. 430.—*Osage Echinoderms*: *a-c*, crinoids; *a*, *Barycrinus hoveyi* Hall; *b*, *Eretnocrinus remibrachiatus* (Hall), having peculiar spatulate arms; *c*, *Actinocrinus lobatus* Hall, shows highly ornamented plates; *d*, *Forbesiocrinus wortheni* Hall, a flexible crinoid; *e*, a blastoid, *Oligoporus mutatus* Keyes.

meaning is not altogether clear. The crinoids made large contributions to the limestone of the period, the "encrinital limestone" taking its name from the numerous plates and stems which make up much of its substance. Other echinoderms were not very abundant.

It is a matter of surprise that the corals had so small a place in this fauna, in view of the favorable physical conditions. It is

probable that the explanation of their paucity lies in organic conditions or relations,—perhaps in the corals themselves, perhaps in unrecorded enemies, or perhaps in the preoccupation and rivalry of the crinoids. *Brachiopods* (Fig. 431), as usual, held a leading place in the fauna, and some of their species ranged to the eastern

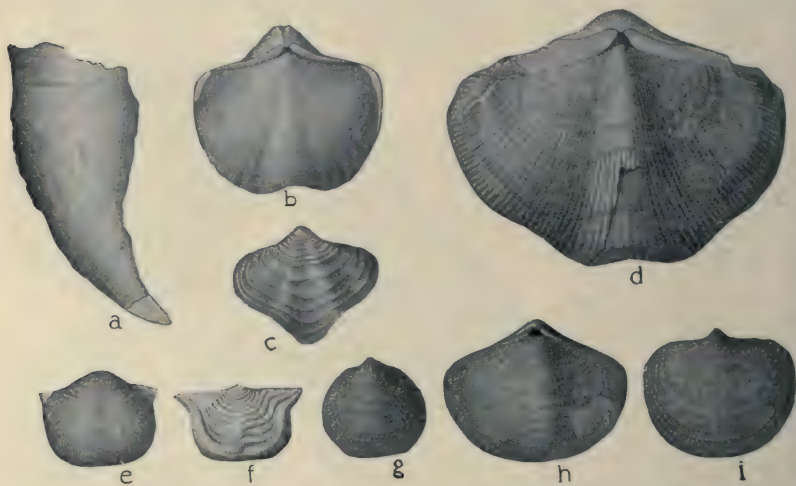


Fig. 431.—*Osage Fossils*: *a*, *Zaphrentis centralis* E. and H., the most characteristic coral of the Osage. *b-i*, brachiopods: *b*, *Spirifer suborbicularis* Hall; a closely allied species occurs in Europe. *c*, *Athyris lamellosa* L'Eveille, a species common to America and Europe; *d*, *Spirifer logani* Hall, the American representative of *Spirifer striatus* of the European Mountain limestone; *e*, *Productus burlingtonensis* Hall, a species abundant in the Lower Osage; *f*, *Leptaena rhomboidalis* Wilck, a species which persisted from the Ordovician to the Osage; *g*, *Rhipidomella burlingtonensis* (Hall); *h*, *Reticularia pseudolineata* (Hall), a spire-bearing brachiopod having a closely allied species in the European Mountain limestone; *i*, *Schizophoria swallovi* Hall, one of the last representatives of the orthids.

continents. *Mollusks* were subordinate, a few winged *pelecypods*, a few capulid *gastropods*, an occasional *pteropod*, and an even rarer *cephalopod*, making up the poor representation of this class. There were a few lingering *trilobites* and some other crustaceans, an ample growth of *bryozoans*, some supposed *sponges* and doubtless many forms not readily fossilized. Marine plants left but an obscure record.

The Waverly fauna. Contemporaneous with the evolution of life in the Kinderhook and Osage seas, there was a rather more provincial development east of the Cincinnati axis. There was no impenetrable barrier between this tract and the sea farther west, but, owing partly to the partial separation and more perhaps to other physical conditions, the fauna east of the Cincinnati arch was somewhat distinct from that west of it.

The Waverly fauna was the direct descendant of the Devonian faunas that had occupied the same ground, and had changed but slowly, as the environment remained nearly constant. It was modified by some immigration of the Kinderhook and Osage types, and took on slowly a Mississippian aspect, while retaining many Devonian characteristics. Its most prominent members were the *pelecypods*, as might have been anticipated from the silty conditions. Many of them were the same as the late Devonian of the same region. *Brachiopods* were numerous and similar to those of the Kinderhook and Osage faunas. The other forms were not very different from those of the more open sea to the westward.

The Waverly fauna was characterized negatively by the rarity of both *corals* and *crinoids*, the apparent reason being their dependence on clear seas. Locally, however, crinoids abounded.

The Great Basin fauna. It will be recalled that the Great Basin was a province by itself in the Devonian period, where a slow faunal development of provincial aspect took place, modified slightly by foreign contributions. The transition from the Devonian to the Mississippian fauna seems to have been gradual, and effected through the progressive evolution of some forms, the elimination of others, and the immigration of a few from westerly sources, and after the Osage epoch, perhaps from easterly sources as well. At the close of the Osage epoch, the Basin fauna united with the Osage fauna to form the Genevieve (St. Louis-Kaskaskia) fauna of the interior.

Previous to this union, one of the most salient distinctions between the Great Basin fauna and the Osage fauna was the rarity of *crinoids* in the former. Although the Osage sea stretched westward to the mountains at least, and was prolific in crinoids, they do not seem to have invaded the Great Basin sea, a fact which

points to the distinctness of the two provinces. *Brachiopods* were abundant in both provinces, but the species were different. The large spirifers so characteristic of the Osage fauna and of the "Mountain Limestone" of Europe were absent. On the other hand, there had arisen, under the genus *Productus*, probably by parallel evolution, species closely allied to some found in the Osage fauna, implying that the Great Basin fauna was taking part, in a conservative way, in evolutionary progress. Were it not for such forms of Mississippian aspect, and the evidence that developed when the two faunas commingled, the Great Basin fauna of this time might be thought to be Devonian, for many species of marked Devonian aspect remained.

Another point of contrast with the Osage fauna was the abundance of the *pelecypods* as compared with the brachiopods. The pelecypod species seem to have been peculiar to the Great Basin sea, and doubtless originated there, and finally became extinct without migration. There were also many *gastropods*, among which were air-breathers, the oldest aquatic pulmonates known, though terrestrial pulmonates have been described from Devonian strata. *Cephalopods* were not abundant. *Trilobites* were about as rare as in the eastern fauna, and of the same genera. *Corals* were present in some abundance, the horn-shaped type predominating. Neither bryozoans nor fishes have been reported. Unless this is due to the imperfection of the record or of present investigation, it adds much to the evidence of the distinctness of the province, for fish abounded in the eastern sea, and they are free-moving forms of migratory habits.

As remarked in the physical discussion, the barrier which enforced the distinctness of the Great Basin and the Kinderhook-Osage seas appears to have been an elongated insular tract lying between the Rocky Mountains and the Great Basin. The yielding of this barrier about the close of the Osage epoch, by erosion or submergence, permitted this singular semi-Devonian, semi-Mississippian fauna of the west to invade the greater eastern sea. The commingling of the two faunas gave rise to the Genevieve¹ fauna

¹ The Genevieve fauna is not restricted to the St. Genevieve limestone.

of the interior. It flourished while the St. Louis and Kaskaskia formations were being deposited.

The Genevieve (St. Louis-Kaskaskia) fauna. As already stated, the St. Louis formation marks the stage of maximum sea-extension in the interior of North America, and the Kaskaskia deposits represent a narrowing and shallowing sea. The Genevieve fauna, representing the two stages, may be regarded as including the culmination of the cosmopolitan evolution of the marine life of the Mississippian period on the North American continent, and

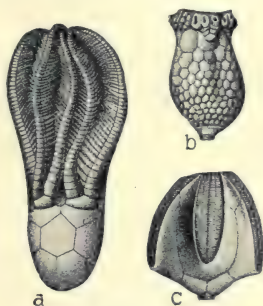


Fig. 432. — *Genevieve Echinoderms*: a, *Agassizocrinus dactyloformus* Shum., a crinoid which lost its stem and became a free swimming creature, at least in its adult condition; b, *Acrocrinus amorphus* W. and Sp., a specialized camerate crinoid with a large number of supplementary plates introduced between the basal and radials; c, *Pentremites robustus* Lyon, a blastoid.

the initiation of its decline. The commingling of the Great Basin and the Osage faunas was the most distinctive feature of the Genevieve fauna. It introduced into the main Mississippian sea what seemed to be a retrograde change, for species of a Devonian aspect that still lived in the isolated Great Basin province and elsewhere, migrated eastward, and their relics are found with species whose evolution had reached an advanced Mississippian phase.

Crinoids were less plentiful than in the Osage fauna, and notably changed (Fig. 432). Of one group which had upwards of 300 species in the Osage fauna, less than 25 species are known in the Genevieve, and among the 25, no Osage species persisted. Other groups of crinoids, however, did not show so remarkable a decline

and new and curious forms appeared. The *blastoids* had their climax here so far as numbers of individuals are concerned, although there was greater generic diversity in the Osage faunas. The leading genus, *Pentremites* (Fig. 432), was so prolific in individuals in some beds as to give rise to the name *Pentremital limestone*. A swift decline seems to have followed this climax, and the beautiful

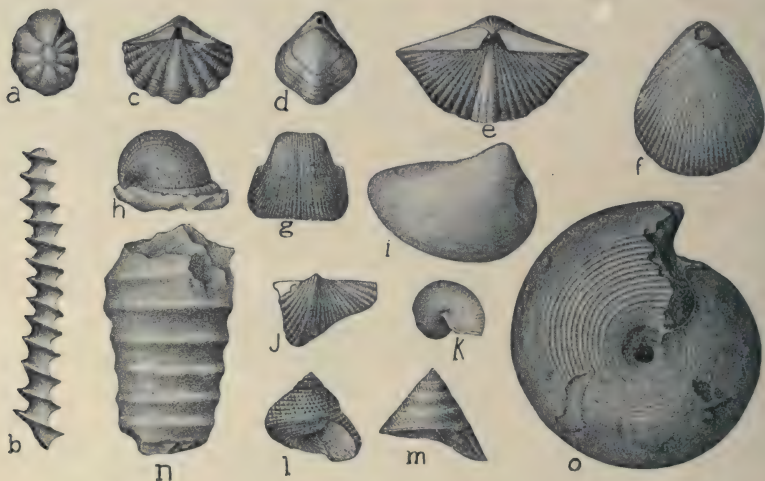


Fig. 433. — Characteristic Genevieve (Upper Mississippian) Fossils: *a*, *Endothyra baileyi* Hall, a small foraminifer, much enlarged, abundant in the Bedford limestone of Indiana, and often mistaken, in the past, for an oölitic concretion; *b*, *Archimedes swallovanus* (Hall), a bryozoan having a peculiar screw-like axis for the support of the colony. *c-h*, brachiopods: *c*, *Spiriferina spinosa* (N. and P.), a genus which developed from *Spirifer*, and has its greatest development in the late Mississippian and Pennsylvanian; *d*, *Seminula subquadrata* (Hall), a species closely related to Pennsylvanian types; *e*, *Spirifer increbes-cens* Hall, a species characteristic of the later Genevieve faunas; *f*, *Eumetria marcyi* (Shum.), a representative of a genus abundant in the Genevieve faunas. It was present in the Kinderhook, but has not been found between the Kinderhook and the closing stages of the Osage; *g*, *Productus fasciculatus* McCh.; *h*, *P. marginicinctus* Prout; *i* and *j*, pelecypods: *i*, *Schizodus chesterensis* M. and W.; *j*, *Conocardium prat-tenanum* Hall; *k-m*, gastropods: *k*, *Bellerophon sublaevis* Hall; *l*, *Pleurotomeria nodulostriata* Hall; *m*, *Eotrochus concavus* Hall. *n* and *o*, cephalopods: *n*, *Orthoceras annulato-costatum* M. and W., one of the an-cient type of straight cephalopods, occasional species of which per-sisted to the end of the Paleozoic; *o*, *Goniatites kentuckiensis* S. A. M. The goniatites reappeared in the Genevieve faunas, though absent from the Osage.

forms disappeared for reasons quite unknown. In the Osage and Genevieve faunas, *echinoids* for the first time showed signs of the prominent development they were to attain later.

Polyps seem to have profited by the decline of the rival crinoids, or by other conditions, for they were more numerous than in the Osage fauna. A compound coral (*Lithostrotion canadense*) became conspicuous in the St. Louis limestone at some localities. Aside from this, the simple horn-shaped forms remained the most common.

Bryozoans made a new departure in their mode of support. The delicate branches of their colonies could not extend themselves indefinitely without special means of support. As one mode of securing this support, the genus *Archimedes* (Fig. 433), which made its first appearance in the Osage, secreted an axis with a spiral flange upon which the colony spread itself, producing a unique form whose slight resemblance to Archimedes' screw gave it name. *Archimedes* became so abundant in the Kaskaskia epoch that a part of the series is known as the *Archimedes* limestone, on account of the great abundance of the fossils of this genus.

For the first time there is clear evidence that the *protozoans* were an important factor in the fauna, though it is not to be understood that they were not really plentiful before; but they are here recorded in certain limestones (p. 598) of the St. Louis series, some layers of which are almost wholly composed of foraminiferal shells of one species (*Endothyra baileyi*, Fig. 433).

A notable modification took place in the brachiopods (Fig. 433), though *Productus* (g and h) continued to be abundant and characteristic. Many large spirifers disappeared, though small ones remained. An odd feature was the diminutive size of the brachiopods in the Bedford limestone of Indiana at Spergen Hill and elsewhere. The associated fossils of other kinds were also dwarfed, implying pauperizing conditions of some sort, for the species seem to be identical with those that grew larger elsewhere. It is not improbable that this limestone was deposited in a partially isolated body of water that was so highly charged with lime and other salts as to be somewhat unfavorable to life. A similar dwarfed fauna is recorded from Idaho.

Among *mollusks*, *pelecypods* (Fig. 433) were rather abundant, and in some of the sandy and silty beds predominated. Some of them still retained a Devonian aspect, and those in the Indiana foraminiferal limestone were diminutive, like the brachiopods. *Gastropods* were more diversified than in the Osage fauna, and some Devonian genera which had apparently been absent from the Osage reappeared. The *cephalopods* (Fig. 433) also were more abundant than they had been in the Osage. *Trilobites* were almost

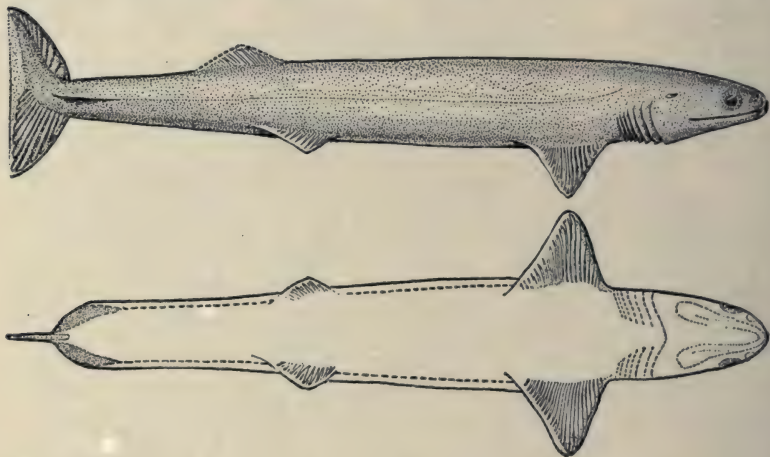


Fig. 434.—*Cladoselache fylei* Newb. Restoration by Dean. About one-fifth natural size. From Cleveland Shales, Ohio. Often referred to the Devonian.

unknown, and the other crustaceans left an unimportant record. *Sharks* were important and other *fish* were present.

The most striking peculiarity of the fauna, it may be repeated, resulted from the invasion of the more conservative fauna of Devonian aspect from the sea of the Great Basin, and perhaps from a similar incursion of lingering forms from the Waverly gulf on the east. The remarkable thing is that these should have succeeded, so far as they did, in impressing themselves on the composite result, and in giving tone to the whole. It is more natural to expect an antiquated fauna to be overwhelmed by a younger and more progressive one. It would be interesting to know what happened from

the counter-migration of the Osage fauna into the Great Basin region; but this has not been determined.

This persistence of Devonian types through to the end of the Mississippian period, taken with the close continuity of the life of the last Devonian epoch with that of the first Mississippian epoch, and the absence of any notable physical break at that point, raises the question whether the Mississippian might not better have been regarded as the later portion of the Devonian period. This would have given to the united period a cosmopolitan climax in the life of the Osage-St. Louis limestones, and a fitting close in the decline of many forms, and the unconformity at the top of the Mississippian. The connection of the Mississippian with the Devonian, whether physically or faunally, is closer than its connection with the Pennsylvanian. But no divisions of a history, which is in reality continuous, can be altogether without infelicities. The pulsations of the history, which alone are the true basis of natural divisions, are rarely the same everywhere at the same time.

With the close of the Mississippian period, the chief center of life interest passes from the sea to the land, first to the vegetation of the Coal period, and then to the land vertebrates. The history of the marine invertebrates will hereafter be followed with less fullness. With the introduction of fishes it had reached its great adjustments, and its further history bears a close likeness to the struggles and adaptations of the history already sketched.

*The Evolution of the Fishes in the Mississippian Period*¹

Many of the ancient invertebrates were as fixed as plants, and their migrations were confined to their early stages; but the fishes were constant rovers of free and rapid movement. While restrained by conditions of food, temperature, etc., they were relatively independent of local conditions. They appear to have effectually invaded the open sea for the first time in the Devonian period, but at that time true marine fishes seem to have been inferior, in number and variety, to those of the inland waters. But by the middle of the Mississippian period, the marine fishes had made such relative

¹ References: Newberry, *Paleontology of Ohio*, Vols. I and II; Woodward, *Vertebrate Paleontology*; Dean, *Fossil Fishes*.

progress that they were in unquestioned supremacy, while the fresh-water forms had declined notably, so far as the record shows. The extension of the epicontinental seas, and the consequent reduction of the land-areas, and doubtless of the land-waters, favored the former and restricted the latter. In the seas the supremacy of the sharks was almost uncontested. They were more abundant, apparently, than in any later period. Up to 1889, about 400 species had been reported from the Mississippian formations of America, and about 200 additional species from Europe.¹ The fossils are chiefly teeth, spines, and dermal ossicles. Three-fourths of the species had crushing or pavement teeth, adapted to breaking the shells of mollusks and crustaceans, and the trituration of seaweeds. The tooth-pavement was formed of large plates of thicknesses ranging up to one and one-half inches, composed of solid dentine below and a thick sheet of enamel above, which was pitted, ridged, or otherwise roughened. The number of spines preserved is exceptionally great when compared with the teeth and dermal ossicles, and implies that the spines were more numerous than in later times. The subsequent loss of spines, like the loss of the plates and other clumsy defensive devices, was compensated for by a gain in agility, intelligence, and more effective weapons of attack. But the great development of species at this time doubtless had its special reason in the fact that most of the sharks were provided with pavement teeth, which were ineffectual weapons against other sharks armed with piercing and cutting teeth. The spines of the one group were therefore a defense against their aggressive kin. The arthrodirens and lung fishes had declined, as compared with the Devonian period.

Of the fishes frequenting the inland and coastal waters, probably the culminating type was of the order to which the modern garpike belongs. The curious tribe of ostracoderms (p. 590) had nearly or quite disappeared.

The fishes probably made up the whole, or nearly the whole, of the vertebrate fauna of the seas. The ostracoderms may have entered the sea, but they were probably fresh-water forms in the

¹ Newberry, *Paleozoic Fishes of North America*, Monogr. XVI, U. S. Geol. Surv., 1889.

main. There are reasons for thinking that amphibians frequented the fresh waters and the adjacent lands, but probably not the seas.

II. *The Land Life of the Mississippian*

Since the period was one of sea extension and its known deposits mainly marine, the record of land life is poor. There was doubtless some notable restriction of the terrestrial life by reason of the encroachment of the sea. Enough fossil vegetation has been recovered to show that the plant life of the early Mississippian land was little more than an expansion of that of the preceding period. There were, however, notable changes in detail. The geographic diversity of the Mississippian floras was somewhat greater than that of the Devonian floras. The mid-Mississippian flora is thought by White¹ to have had its origin on the islands of western Europe, and to have spread thence to Siberia and southward, even to South Africa and Australia; but by what route is not known with certainty. Seventy-five per cent of the species of a Mississippian flora of Argentina are identical with European species, a fact which suggests strongly a land bridge between South America and the continents just named.

The floras of the early and middle parts of the period are better known than those of its closing stages. The flora of the latter indicates adverse conditions of life, and prepares the way for the great floral changes, largely exterminative, which followed. From this stage comes the only American pre-Permian wood (*Dadoxylon pennsylvanicum*) which shows rings.

The most interesting suggestion of advance in land life is found in the footprints of a supposed amphibian (*Peleosauropus* [*Sauropus*] *primævus*) from the Mauch Chunk shale near Pottsville, Penn. They imply a stride of about thirteen inches, and a breadth between outer toes of eight inches. Nearly complete specimens of amphibia (*labyrinthodonts*) have been found in the Lower Carboniferous of Scotland.

Probably the insects and their allies found in the preceding system were represented, but their fossils are not known to have been found.

¹ Jour. of Geol., Vol. XVII, 1909.

CHAPTER XXI

THE PENNSYLVANIAN (UPPER CARBONIFEROUS) PERIOD

FORMATIONS AND PHYSICAL HISTORY

The most distinctive feature of this system in North America is its content of coal in the central and eastern part of the United States. It includes the Pottsville conglomerate (Millstone grit) below, and the Coal Measures above.

THE POTTSVILLE CONGLOMERATE (MILLSTONE GRIT)

The lowest formation of the system in the Appalachian region is generally sandstone or conglomerate, having different names in different regions. From its conglomeratic phase in the east, it grades into sandstone at the west, and with local conglomeratic phases, the sandstone persists over the interior. It has not been recognized in the western part of America. Over wide areas it is unconformable on the Mississippian system, as already noted, and in places it appears to be a true basal conglomerate. In some places it is made up partly of cherts derived from the Mississippian limestone, showing that the latter had undergone prolonged decay before the deposition of the conglomerate. In other places the pebbles of the conglomerate seem not to have had a local origin. This argues for wide-spread emergence before the epoch of the Millstone grit, for on land, streams shift materials great distances. Locally as in Illinois, the formation is oil-bearing.

At various points in the east the formation contains thin beds of coal showing the local beginnings of the conditions which existed later over wide areas, and in the southern Appalachians it is an important source of coal.

The formation varies in thickness from a maximum of some 1,500 feet in the Appalachians, to less than 100 feet in some parts of

western Pennsylvania. The unequal thicknesses, even where the formation has not suffered from erosion, are due partly to the unevenness of the eroded surface on which it rests, partly to unequal rates of sedimentation, and partly to unequal duration of the time of sedimentation in different regions. The formation is usually so firmly indurated that the outcrops of its tilted beds have become ridges.

THE COAL MEASURES

Above the Pottsville conglomerate and its equivalents in the central and eastern parts of the continent, lie the formations known collectively as the Coal Measures. They consist of a succession of alternating beds of shale, sandstone, conglomerate, limestone, coal, and iron ore. The succession differs greatly in different regions, but shale and sandstone perhaps recur more frequently than any other members of the series, and in thicker beds. Both the coal and some of the iron ore are in layers interstratified with the other members of the series, and are to be looked upon as strata of rock. Important as the coal and iron ore are from an economic point of view, they make up but a small part of the Coal Measures. Although there are many beds of coal in some regions, and although some of them have great thickness (40 to 50 feet), the proportion of coal in the Coal Measures is rarely so much as 1:40, and that of iron ore is much less. The classification of the Pennsylvanian and Permian systems of the east now in common use is as follows:¹

	<i>Present</i>		<i>Old</i>
Permian	Dunkard formation (or series)	=	Upper Barren Coal Measures
Pennsylvanian	4. Monongahela	" " "	= Upper Productive Coal Measures
	3. Conemaugh	" " "	= Lower Barren Coal Measures
	2. Allegheny	" " "	= Lower Productive Coal Measures
	1. Pottsville	" " "	

A twofold division is common farther west. Thus in Iowa the lower division is called the *Des Moines*, and the upper, the *Missouri*.

¹ Prosser, Am. Jour. Sci., 4th series, Vol. XI, p. 191, 1901. For recent review of the Pennsylvanian system of the Appalachian region, see Stevenson, Bull. G. S. A., Vol. XVII.

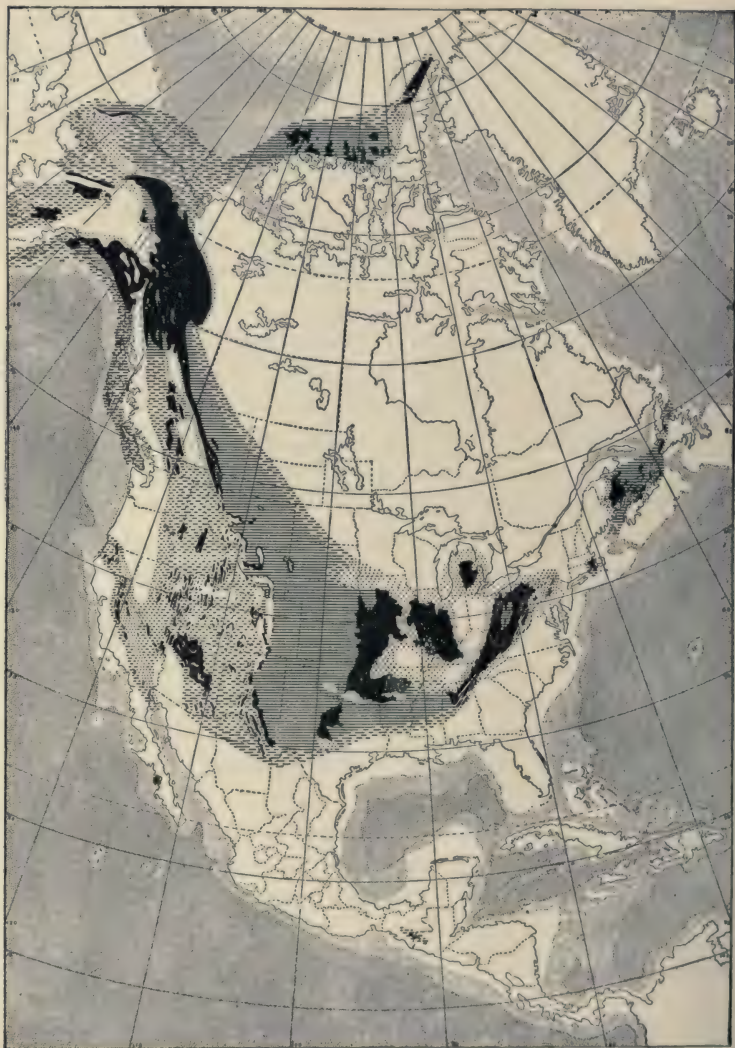


Fig. 435.— Map showing the areas where the Pennsylvanian system appears at the surface in North America. The map also shows, as in preceding similar cases, the areas where the Pennsylvania system is thought to exist though buried (lined areas); the areas where it is thought once to have existed, but to have been removed by erosion (dotted); and by implication the relations of land and sea during the Pennsylvanian period.

*an.*¹ In other regions, as in Ohio, a fourfold division was formerly made, as shown in the table above, but the uppermost is now generally referred to the Permian.

Distribution and outcrops between the Appalachians and the Rockies. The distribution of the unburied part of the Pennsylvanian system is shown in Fig. 435; also the areas where the system is believed to exist, though concealed, and where it is thought to have been removed by erosion. The system is probably concealed in areas to the south of those shown on the map, and its equivalent doubtless underlies much of the sea.

The surface distribution of the system in the eastern part of the continent is in some ways in sharp contrast with the surface distribution of older systems. The commonest position for the outcrops of the preceding Paleozoic systems severally is around the outcrops of older systems. But the outcrops of the Pennsylvanian exhibit no tendency to a similar concentric distribution. Rather do they seem to cover areas between the outcrops of older formations. Thus in Michigan, the Pennsylvanian strata occupy an area completely surrounded by older formations.

This difference in surface distribution does not betoken any new principle in the distribution of the system. The Ordovician formations come to the surface, among other places, in New York, Ohio, Wisconsin, Missouri, and the Black Hills. Beneath the surface, the beds outcropping in these several localities are believed to be continuous, though concealed by younger formations. It will be remembered that most of the eastern interior, and perhaps most of the west as well, became land at the close of the Ordovician period. Had it never been submerged again, the Ordovician system would not have been covered, and its outcrops would now have appeared at the surface in broad areas between the outcrops of older formations; that is, its outcrops would have corresponded, in principle, with the surface distribution of the Pennsylvanian. After the deposition of the Pennsylvanian system, the surface where it is now exposed was elevated, relatively, and except for the glacial drift, was either never deeply covered by later deposits, or the overlying formations have been removed. Some of the separate

¹ Geol. Surv. of Iowa.

areas of the system shown in Fig. 435 have probably been isolated by erosion since their deposition.

PRODUCTIVE COAL-FIELDS

The Pennsylvanian system does not contain coal in workable quantity everywhere, though coal is widely distributed as far west as the 96th or 97th meridian in Oklahoma, and nearly to the 100th meridian in Texas. The productive coal areas of the system in the United States are five in number. These are as follows¹:

(1) *The anthracite field*, which is confined to eastern Pennsylvania, and contains an area of 484 square miles. It includes

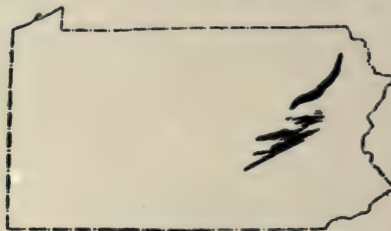


Fig. 436.— Map showing the areas of anthracite coal in Pennsylvania.



Fig. 437.— Section across Panther Creek basin in the anthracite region of Pennsylvania, showing the position of the strata and the coal beds, in black. (Stoek, U. S. Geol. Surv.)

several elongate, nearly parallel, synclinal basins, the longer axes of which have a northeast-southwest direction (Figs. 436 and 437). From the adjacent anticlines, and from the neighboring shallower synclines, the coal-bearing beds have been removed by erosion. The strata of this field may once have been continuous with those of the next.

¹ Hayes, Stoek, White, Campbell, Haseltine, Lane, Ashley, Bain, and Taff, 22d Ann. Rept., U. S. Geol. Surv., Pt. III, p. 15.

(2) *The Appalachian field*, which extends from the northern border of Pennsylvania to central Alabama, a distance of about 850 miles (Fig. 438), embraces an area of about 70,000 square miles, of which about 75 per cent contains workable coal. Speaking in general terms, the western edge of the sharply folded Appalachian belt forms the eastern edge of the Appalachian coal-field. With few exceptions, the strata of this field are gently undulating or

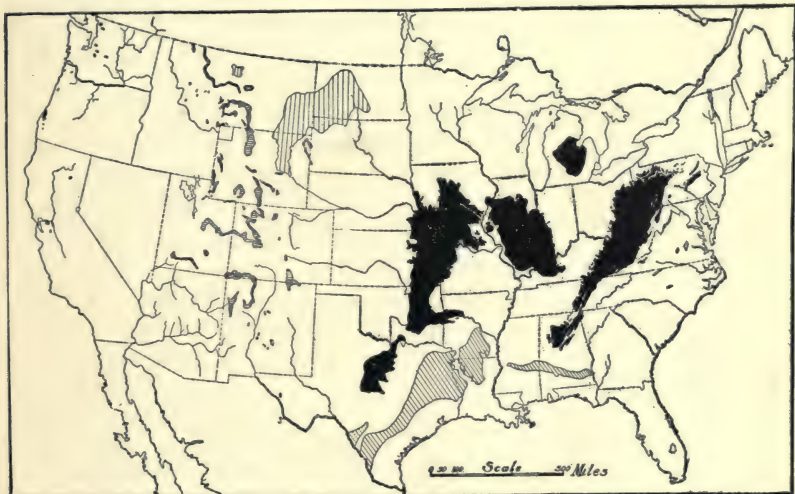


Fig. 438.— Map showing the known distribution of coal in the United States. The black areas are the areas within which coal of the Pennsylvania system (anthracite and bituminous) occurs. The areas marked by dots in Virginia and North Carolina, represent Triassic (bituminous) coal. Those with vertical (lignite) and horizontal (anthracite, bituminous, and lignitic-bituminous) lines represent coal of the Cretaceous (Laramie) system, and those with diagonal (lignite) and crossed (bituminous and lignitic-bituminous) lines represent coal fields of Tertiary age. Some of the fields, as those of Washington and California, appear very small on this map. The Cretaceous and Tertiary areas include only those where there is known to be workable coal. (U. S. Geol. Surv.)

horizontal. Few beds of coal are known to have great extent, but the Pittsburg bed in the Monongahela series, and the Sewanee bed in the Pottsville, seem to be continuous over areas of several thousand square miles.

(3) *The Northern Interior field*, confined to the southern peninsula of Michigan, covers an area of about 11,000 square miles. The

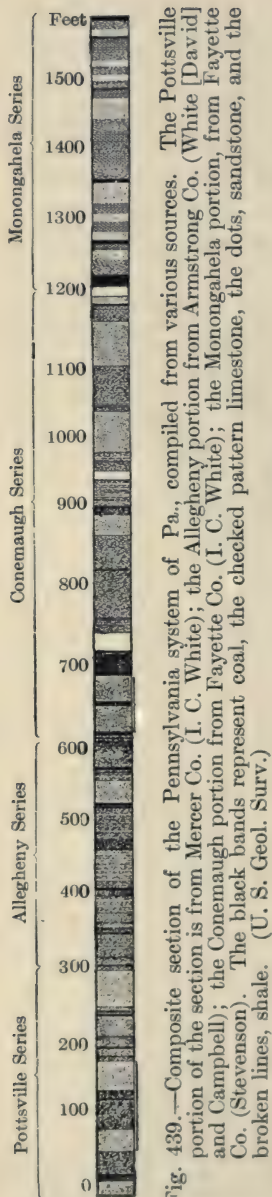


Fig. 439.—Composite section of the Pennsylvania system of Pa., compiled from various sources. The Pottsville portion of the section is from Mercer Co. (I. C. White); the Allegheny portion from Armstrong Co. (White [David] and Campbell); the Conemaugh portion from Fayette Co. (I. C. White); the Monongahela portion, from Fayette Co. (Stevenson). The black bands represent coal, the checked pattern limestone, the dots, sandstone, and the broken lines, shale. (U. S. Geol. Surv.)

strata of this field appear to dip gently toward the center of the basin (i. e., toward the center of the Lower Peninsula). The formations of this basin were probably never connected with those of the other coal-fields.

(4) *The Eastern Interior field* covers an area of about 58,000 square miles in Indiana, Illinois, and Kentucky (Fig. 438), and about 55 per cent of it is productive. This field is set off from the Appalachian field on the east, and from the Western Interior field on the west, by broad low anticlines from which the Coal Measures, if ever present, have been eroded. It is probable that this field was once connected with the next, and perhaps with the Appalachian field.

(5) *The Western Interior and South-western fields* constitute a nearly continuous area of Coal Measures formations, stretching from northern Iowa to central Texas, a distance of 800 miles, and covering an area of 94,000 square miles. On the east this field is limited by the broad low anticline which borders the Eastern Interior field on the west. It is limited on the west by the overlap of younger formations. Except in Arkansas and Oklahoma, where the strata are folded, the beds of the Coal Measures of this area are essentially horizontal.

East of the Appalachians. *The Nova Scotian-New Brunswick coal-field* lies on either side of the Bay of Fundy and contains an area estimated at about 18,000 square miles. The coal is bitu-

minous and of good quality. The system here attains a thickness of 13,000 feet.

In the vicinity of Narragansett Bay,¹ the Carboniferous system has great thickness, and often rests on beds of Cambrian age. Coal occurs here, but it is too highly anthracitic (or graphitic) to burn readily. The beds are much deformed and are associated with igneous rocks. Carboniferous rocks of undetermined extent occur at other points in New England, where they are partly igneous (Fig. 441) or meta-igneous, and partly meta-sedimentary. They

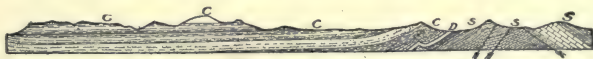


Fig. 440.—Section showing the position and relations of the Carboniferous section near Estillville, Ky. *C* = Carboniferous (including Mississippian); *D* = Devonian; *S* = Silurian. Length of section about 16 miles. (Campbell, U. S. Geol. Surv.)

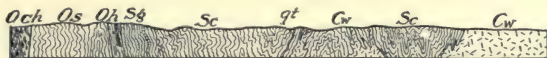


Fig. 441.—Section in southwestern Massachusetts, showing the position and relations of the Carboniferous system. *Cw* = igneous rock, Carboniferous; *Sc* (Conway schist) and *Sg* (Goshen schist) are Silurian formations; *Oh* (Hawley schist), *Os* (Savoy schist), and *Och* (Chester Amphibolite) are probably Ordovician, though classed with the Silurian in the Hawley folio. (Emerson, U. S. Geol. Surv.)

are so completely metamorphic in some places as to make the determination of their age and relations difficult and uncertain. Beds of this age have recently been recognized in the Piedmont of Alabama.²

Distribution west of the Great Plains. The Pennsylvanian system is wide-spread west of the Great Plains, and probably underlies the Plains themselves. With rare exceptions, the western beds, largely of limestone and sandstone, are coal-less. The coal-less phase of the system, the whole earth considered, is far more wide-spread than the coal-bearing. The abundant coal of the west belongs to later systems.

¹ Shaler, Woodworth, and Foerste, *Geology of the Narragansett Basin*, Mono. XXXIII, U. S. Geol. Surv.

² Smith, E. A., *Underground Water Resources of Alabama*, Geol. Surv. of Ala., 1907.



Fig. 442.—Section showing position and relations of the Carboniferous system (as well as others) in the Yellowstone Park. *A* = Archean, *C* = Cambrian, *S* = Ordovician and Silurian, *D* = Devonian, *C* = Carboniferous, *J* = Jurassic, *K* = Cretaceous, *N* = Neocene, and *anp* = igneous rock. Length of section about 17 miles. (Hague, Iddings, and Weed, U. S. Geol. Surv.)

The Mississippian and Pennsylvanian systems of the west have commonly been grouped together under the name Carboniferous. Most of the formations of both systems are marine, but sedimentation was somewhat generally interrupted at the close of the Mississippian period (p. 602). The formations of the Pennsylvanian period are not in general so wide-spread as those of the Mississippian, in this part of the continent.

In some parts of the west, the Carboniferous system includes formations which resemble the "Red Beds" of the next (Permian) system. This is the case, for example, in the southern part of the Rocky Mountain region, and in the plains adjacent, and here the separation of the Pennsylvanian system from the Permian is not very distinct or has not been carefully worked out.

The Carboniferous system of the west includes all sorts of sedimentary rocks, among which are considerable thicknesses of limestone. They are exposed at many points (Fig. 435) and their existence over wide areas where they are now covered by later deposits is certain. The system is, however, not continuous. Numerous islands of older rock probably maintained themselves throughout the period, and a large area of land existed throughout the Paleozoic era in western Nevada (west of long. 117°), and had an unknown extension north and south.

Many of the outcrops of the system in the west are about areas of older rock, and it is not always possible to tell whether these older formations were islands in the Carboniferous seas, or whether they once had overlying formations, now removed.

Figs. 442 to 444 show the positions and relations of the Mississippian and Pennsylvanian systems at various points in the west. In most cases the sections are from regions where the strata have been much disturbed by folding, faulting, and the irruption of igneous rock.

North of the United States, Carboniferous strata (largely Mississippian) outcrop on the west side of the northward continu-



Fig. 443.—Section showing the position and relations of the Carboniferous system at a point in Colorado. *R* = Archean; *C* = Cambrian (Sawatch quartzite); *O* = Ordovician (Yule limestone); *M* = Mississippian (Leadville limestone); *Cw* (Weber formation) and *Cm* (Maroon conglomerate) = Carboniferous; *J* (Gunnison formation) = Jurassic; *Kd* (Dakota formation), *Kb* (Benton shale), *Kn* (Niobrara limestone), and *Km* (Montana formation) = Cretaceous. Length of section about 6 miles. (Eldridge, U. S. Geol. Surv.)

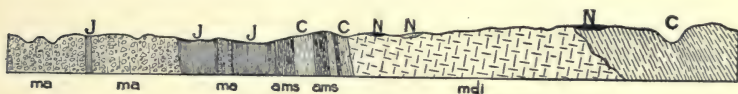


Fig. 444.—Section showing the Carboniferous in the Sierras of central California. *C* (Calveras formation) = Carboniferous; *J* (Mariposa slates) = Jurassic; *mdi* = metadiorite; *ams* = amphibolite schist; *N* = igneous rock of various sorts, of Neocene age. Length of section about 6½ miles. (Ransome, U. S. Geol. Surv.)

ation of the Great Plains, and the strata here are probably continuous beneath younger beds which occupy the surface between them, and they are probably also continuous to the southward with the contemporaneous formations of the United States. Strata of the same age are found on both sides of the Gold Range of British Columbia. West of this range, much volcanic rock, the greater part of which was extruded before the close of the period (p. 601), appears in the system. The system is continued northward into Alaska,¹ where it is less wide-spread than the Mississippian, so far

¹ Brooks, Professional Paper 45.

as present knowledge goes. In the Arctic lands of America, the Mississippian and Pennsylvanian are not differentiated, but one or both are somewhat wide-spread.

Thickness. The thickness of the Pennsylvanian system has a wide range, but like all preceding systems of the Paleozoic, it is especially thick (4,000 to 5,000 feet) in the Appalachian Mountains. In the interior, the corresponding formations rarely much exceed 1,000 feet; but in Arkansas, the Coal Measures have been assigned the remarkable thickness of more than 18,000 feet, from which it is inferred that there must have been land close at hand capable of supplying sediments in great quantity. This was probably the axis of the Ouachita uplift. In Texas, the thickness of the system ranges up to 5,000 feet, and in the west, the maximum thicknesses exceed all those mentioned above, except that of Arkansas.

COAL

The general conditions under which sandstone, shale, and limestone originate have already been outlined, but there has been no occasion heretofore to consider the formation of coal. From its economic importance, this sort of rock has been studied with more care than most others, and geologists are agreed, in a general way at least, as to its mode of origin.

Origin. There is no doubt that coal is of vegetable origin. Except by the accumulation of vegetable matter, no way is known by which such beds of carbon could be brought into existence. Furthermore, the coal and its associated shales contain abundant remains of plants, sometimes even recognizable tree-trunks in the form of coal, and microscopic study has revealed the fact that the coal itself is often but a mass of altered, though still recognizable vegetable tissues. Concerning the exact manner in which the beds of vegetable matter accumulated, and concerning the conditions under which it was converted into the various sorts of coal, there is some difference of opinion.

Much of the coal is essentially pure, containing little matter of any sort which was not in the plants which gave origin to it. Purity does not mean freedom from ash, since mineral matter, which on

combustion becomes ash, is present in all plants.¹ Along with the large amount of coal which is pure, or nearly so, there is much which contains some admixture of earthy matter. Where the admixture of earthy matter is small, the coal may still be used; but from poor coal of this sort, there are all gradations into carbonaceous shale. Black shales are commonly associated with coal-beds.

The purity of some coal-beds over great areas warrants the conclusion that they were made of vegetation which grew where the coal is. The character of the vegetation of the coal shows that it grew on land or in swamps. Had it been washed down from its place of growth to the situations where the coal is, it should have been mixed with earthy sediment, and the product, after the necessary changes in the vegetable matter, would have been very unlike the purer coal-beds. Furthermore, the nearly uniform thickness of many of the coal-beds over great areas, sometimes many thousand square miles, constitutes a strong objection to the hypothesis that it was drifted together by any process whatsoever.

Some of the facts which support the theory that the vegetation grew where the coal-beds are, may be noted. Thus (1) beneath each coal-bed there is, as a rule, a layer of clay with roots (or root marks) in the position of growth. The clay seems to have been the soil in which the coal vegetation was rooted. (2) In association with the coal-beds, the stumps of trees are sometimes found still standing as they grew (Fig. 445). (3) In the coal-beds, or in the associated layers of shale, imprints of the fronds of ferns or fern-like plants are found. They are often so numerous and so perfect as to indicate that they were buried where they fell, without being drifted by moving waters from one place to another. (4) The layer of rock next overlying a coal-bed often contains abundant remains of vegetation, especially in its lower part, as if the conditions which brought about its deposition resulted in the destruction of the forest growth which had preceded. In such situations, trunks of trees 50 and 60 feet long, and 2 or 3 feet in diameter, are sometimes found. (5) The vegetable matter in and about coal-beds is made up of the trunks, small stems, leaves, and fruits of the various

¹ Many of the modern allies of the coal-plants contain as much as five per cent of ash, and a few much more.

plants concerned, intermingled in such manner and proportions as to indicate that the vegetation grew where the coal now is. If the vegetation had been drifted together, these various constituents would hardly have been left commingled as they are. But while it is confidently believed that most of the workable coal represents the growth of vegetation *in situ*, it is not to be understood that coal was never formed from vegetation which drifted together.

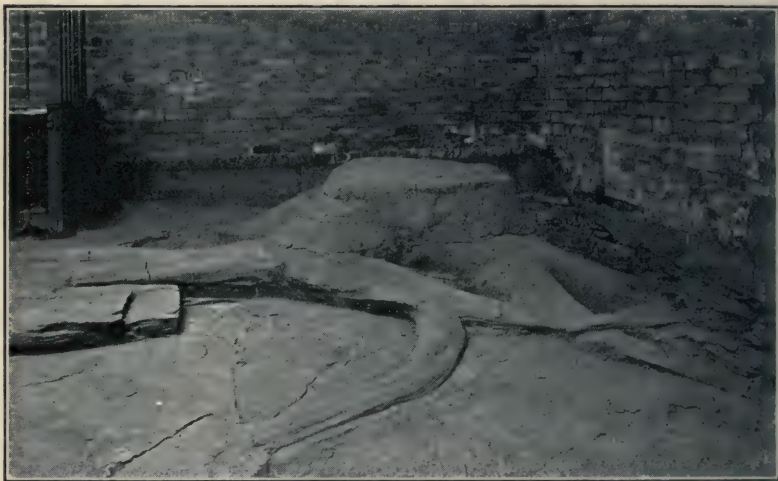


Fig. 445.— Showing a stump standing as it grew in Coal Measures, near Glasgow, Scotland.

In the formation of a coal-bed, three things are to be accounted for: (1) The conditions under which the necessary bodies of vegetation accumulated, often essentially free from the admixture of sediment; (2) how the vegetation was kept from decay; and (3) how it was changed into coal.

The accumulation of organic matter. Large marshes, or marshes in low surroundings, are the only places where vegetable matter is now accumulating in quantity, with little admixture of sediment. Thus in the marshes along some parts of the Atlantic coast (Fig. 446), there are great quantities of organic matter which, locally, is mixed with little sediment. In Dismal Swamp,

the stems, branches, leaves, and fruits of the trees, shrubs, and herbs which grow there, have been long accumulating, and the great mass is nearly free from sediment. In various cypress and mangrove swamps, too, there are considerable thicknesses of vegetable matter nearly free from mud, etc. The multitude of marshes and peat-bogs in the United States and Canada are further illustrations of the accumulation of vegetable matter, sometimes mixed with abundant sediment and sometimes nearly free from it.



Fig. 446.— Map of the Cape May peninsula, showing coastal marshes. The unshaded areas inside the coast line are dry land.

The vegetation in such situations need not be more luxuriant than on moist lands which are not swampy. On fertile prairies and in great forests the annual growth of vegetation is great; but since the leaves, fruits, twigs, and trunks decay as they fall, the larger part of their substance is returned to the atmosphere. In a moist region there is more growth (and therefore more death) of vegetation than in a dry one, and a better chance that decay will not keep pace with death. Decay is less rapid in a cool climate than in a hot one, so that in the former, there is more likely to be a residuum of partially decayed organic matter.

Preservation of vegetable matter. In marshes, where the vegetation falls into water, it usually undergoes slow change different from decay suffered by vegetation which falls on dry land. The preserving influence of water is seen in many ways. Posts and piles set partly in water and partly above, decay just above the water-level, while the portions below remain sound. It is the partial preservation of organic matter in the water of marshes and very shallow lakes which converts them into peat-bogs, for the peat is nothing more than accumulated vegetable matter undergoing those changes to which vegetable matter in water is subject. Under favorable conditions, the peat of a bog may become very deep, as in the Dismal Swamp and elsewhere. In and about marshes and swamps, therefore, we find the conditions for the accumulation of considerable thicknesses of vegetable matter, sometimes nearly free from sediment, and at the same time the conditions which keep it from complete decay.

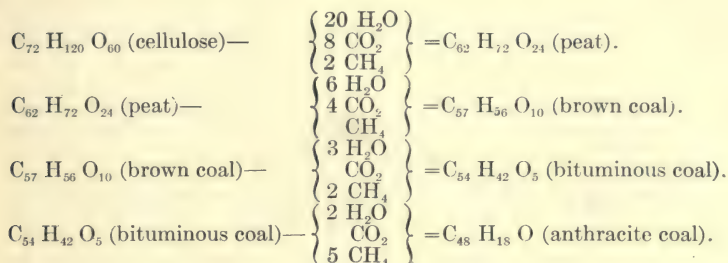
Conversion into coal. But while the vegetable matter is not destroyed, it is not preserved intact. The composition of wood and peat are illustrated by the following analyses (ash omitted), though neither wood nor peat has a constant composition.

	<i>Carbon</i>	<i>Hydrogen</i>	<i>Oxygen</i>	<i>Nitrogen</i>
Wood	49.66	6.21	43.03	1.10
Peat	59.50	5.50	33.00	2.00

The relative atomic proportions of carbon, hydrogen, and oxygen in cellulose are expressed by the formula $C_{72}H_{120}O_{60}$. In the air, the carbon and the hydrogen of the wood unite with the oxygen of the air or the wood itself, forming carbon dioxide and water, the principal products of the decay of vegetation. But under water the atmospheric oxygen is largely excluded, and the elements of the wood are thought to unite with one another to a larger extent, while the oxygen of the air plays but a subordinate part. One of the common products of decay under such circumstances is CH_4 (marsh-gas), which bubbles up from swamps and escapes into the atmosphere. The formation of this gas exhausts the hydrogen of the organic matter four times as rapidly as the carbon. If the carbon of the wood unites with the oxygen of the wood, forming

carbon dioxide, the oxygen is exhausted twice as rapidly as the carbon. If the hydrogen and the oxygen of the wood combine, the result is to increase the proportion of carbon remaining.

While the exact quantitative relations of the reactions which take place are not known, and are probably not constant, the following table¹ suggests certain changes which might take place, and the products which would remain at certain stages:



From this table it will be seen that the process which converts vegetable matter into coal is characterized by progressive changes in the nature of the chemical decomposition. The elimination of hydrogen and oxygen in the form of water probably is the dominating chemical change in the production of peat from cellulose. Second in importance at this stage is the removal of oxygen in the form of carbon dioxide, while the liberation of methane (CH_4) is of still less importance. As the alteration of the peaty material progresses through successive stages to anthracite coal, less and less water and carbon dioxide are given off, and there is a steady increase in the proportion of methane which is freed. Laboratory investigations have shown that while carbon dioxide may constitute an important part of the free gas held within the pores of some of the Cretaceous coals, the gas which escapes from the more advanced stages of Pennsylvanian anthracite coal is largely methane. The burial of the peat compresses it, and the physical change resulting is a part of the process of coal-making.

If the coal-beds represent Carboniferous swamps, as they are believed to, we have still to inquire into the conditions under

¹ Prepared by Rollin T. Chamberlin.

which such extensive swamps existed, and to seek the explanation of their frequent recurrence (one for each coal-bed) in many regions.

The first condition for a swamp is lack of drainage, and the second a sufficient, but not an excessive amount of water. Enough to stop the growth of vegetation would be excessive, and too little to preserve it from prompt decay after its growth and death, would be insufficient.

Summary. In the course of the wide-spread movements which affected the eastern interior at the close of the Mississippian period, great areas appear to have emerged from the sea. Early in the Pennsylvanian period, considerable tracts which were not submerged stood so low as to be ill-drained, or undrained, and constituted marshes. Climatic conditions were such as to permit the growth of abundant vegetation in the marshes. On falling into the shallow water, the vegetable matter underwent changes of the nature suggested above. The marshes were thus converted into peat bogs. Some of the great coal-swamps probably came into existence along the sea-shores, and some in shallow basins or undrained areas remote from the sea, for fresh-water shells are found in association with some coal-beds, and marine fossils with others.

Each coal-bed represents the accumulated vegetable growth of a long period. It would appear that the growth and accumulation of vegetation was often brought to an end by subsidence which let the water (sea, or lake or aggrading stream) in over the marshes, drowning the plants, and burying the organic matter which had already accumulated under deposits of mud, sand, etc., which the submergence brought in its train. A second coal-bed in the same region points to the recurrence of swamp conditions, and means either (*a*) that after submergence and burial of the organic matter, slight emergence reproduced the conditions for bogs; or (*b*) that by sedimentation the sea or lake bottom where the first bog had been was built up to the water-level, restoring swamp conditions.

The number of coal-beds is often great. In Pennsylvania it frequently (but not everywhere) exceeds 20; in Alabama, 35 (not all workable) have been enumerated; in Nova Scotia, the number, including some dirt-beds, is said to be about 80; but in the Missis-

sippi basin west of the Appalachians, the number is often less than a dozen. In Illinois the number of workable beds is nine.¹

Extent and relations of coal-beds. The wide-spread distribution of coal does not mean that any one marsh necessarily covered the whole of any one great coal-field. A few of the coal-beds, however, are of great extent. Thus the Pittsburg coal-bed is worked over an area of some 6,000 square miles² in western Pennsylvania, Ohio, and West Virginia, and has at least an equal extent where too poor to be generally worked. Many coal-beds, on the other hand, do not occupy great areas. From their thicker portions they thin out in all directions, often grading into black shale. From these facts it is inferred that within the general area of a coal-field there may have been elevations (islands) above the marsh level, interrupting the continuity of the swamps, and therefore the coal-beds.

Varieties of coal. The ways in which the different varieties of coal have arisen have never been satisfactorily determined. In general it is true that the anthracite coal occurs in mountainous regions, where the coal and other layers of rock with which it is associated have been subject to more or less dynamic action. Thus, in the mountains of eastern Pennsylvania (Fig. 436) the coal is mainly anthracite, while in the other coal-fields of the same age, where the strata are but slightly deformed, the coal is bituminous. In Arkansas, where the strata have been subject to some, but not to extreme dynamic action, coal is semi-anthracitic.³ Where the metamorphism of the associated rock has been extensive, as in Rhode Island,⁴ the coal has gone beyond the anthracitic stage. Anthracite coal is also found in some places (not in the Coal Measures of the United States) in contact with dikes, in situations like those where other sorts of rock are metamorphosed.

These phenomena long ago suggested that anthracite is meta-

¹ Reports on coal have been published by all states containing coal, where there have been surveys. For local details see reports of Pennsylvania, Ohio, Kentucky, Tennessee, Alabama, Indiana, Illinois, Iowa, Missouri, Arkansas, Kansas, and Texas.

² White, West Virginia Geol. Surv., Vol. II, p. 166.

³ Ann. Rept. Ark. Geol. Surv., 1888, Vol. III.

⁴ Geology of the Narragansett Basin, Mono. XXXIII, U. S. Geol. Surv.

morphic coal, produced from bituminous coal by processes similar to some of those which metamorphose other sorts of rock. The fact that metamorphic coal is usually found in regions where erosion has exposed its beds (Fig. 437) has led to the conjecture that exposure of the coal may be a factor in the problem, the exposure favoring the escape of the volatile constituents, and so aiding in the transformation of bituminous coal to anthracite. Beds of bituminous coal are, however, often freely exposed. Both dynamic action, involving pressure and heat, and exposure would seem to be conditions favoring the development of anthracite, but it does not follow that these are the only factors in the problem, or that anthracite coal has never been produced in other ways. White has recently advanced the idea that deep-seated, horizontal thrust movements are the essential cause of devolatilization.¹

There are several varieties of bituminous (soft) coal, some of which appear to depend on the nature and extent of the decay of the vegetable matter before its burial, and some on the degree to which the devolatilizing processes have been carried since burial. Recent studies² seem to indicate that the kind of vegetation entering into the make-up of the coal may have an important effect on the product. Thus some coal seems to be made up largely of algæ, and such coal has rather distinctive qualities, if present interpretations are correct.

Other Products of Economic Value

Iron ore. The iron ore of the Coal Measures occurs in layers like the coal, or in the form of nodules which are often concentrated at a given horizon, forming a nearly continuous layer. The iron of the Coal Measures seems to have been largely deposited as a precipitate from the waters of inland and local basins while the other members of the system were being laid down. Dissolved by the land waters from the soil and rocks, it was brought to the marshes in some soluble form. In the marshes, it was precipitated either in the form of the carbonate or ferric oxide. Subsequent oxidation has changed some of the original carbonate into ferric oxide. The

¹ David White. *Economic Geology*, Vol. III.

² Especially those of Mr. White.

principal iron ores of the Pennsylvanian system occur in Pennsylvania and eastern Ohio.

The Pennsylvanian system yields *oil and gas* in some places, as in Oklahoma, Kansas, and Illinois.

General Considerations

Geographic conditions in the eastern interior. Returning for a moment to the system of which the coal-beds form an inconsiderable part, it is to be recalled that many of the clastic beds associated with the coal were laid down in fresh water, while other parts of the system were deposited in the sea. It follows that marine, lacustrine, and marsh conditions alternated with one another, and perhaps with land conditions.

The succession of Pennsylvanian beds in southwestern Pennsylvania (Fig. 439) illustrates the great series of changes which took place in sedimentation in the course of the period. The cause of the variation was probably geographic, but it is not to be inferred that geographic changes were more frequent at this time than during other periods. Their record is conspicuous because of the coal; or, in other words, because the land was near sea-level, so that extensive submergence and emergence resulted from slight changes of relative level of land and sea. It should be remembered that equally frequent and equally extensive movements, or that equivalent degradation and aggradation, would leave no such record of themselves, if the surfaces concerned were far above or far below sea-level. It was oscillation just above and just below water-level which allowed the record to be so clearly preserved. How far the oscillations were due to warpings of the land, and how far to changes in the level of the sea, cannot now be determined; but when we recall that the ocean-level must respond to every deformation which affects its bottom (unless compensated by an equivalent opposite movement), and to every stage of filling,¹ it does not seem strange that its level is in a nearly perpetual state of change.

In general, it may be said that the movements of the crust which have been of most importance, from the point of view of continental or biological evolution, are not those which have

¹Salisbury, Jour. Geol., Vol. XIII, p. 469.

affected high land or deep sea bottom, but those which have converted sea bottom into land, or land into sea bottom. Such changes are most likely to have taken place where land was low, or water shallow. From the point of view of geology, therefore, the *critical level* of crustal oscillation is the level of the sea.

Duration of the period. So uncertain is our knowledge of the duration of geological time that all sorts of data which can be made to throw light on the subject are of interest, even though they do not lead to trustworthy numerical conclusions. Under favorable conditions, a foot of peat may accumulate in ten years or even less; but the usual rate is probably much slower. Peat bogs are now in existence in which the depth of the accumulated organic matter is 40 or 50 feet, but the length of time involved is not known. A vigorous growth of vegetation has been estimated to yield annually about one ton of dried vegetable matter per acre, or 640 tons per square mile. If this annual growth of vegetable matter were all preserved for 1,000 years, and compressed until its specific gravity was 1.4 (about the average for coal) it would form a layer about seven inches thick. But a large part of the vegetable matter, even in peat bogs, escapes as gas (CO_2 , CH_4 , etc.), in the making of coal. It has been estimated that four-fifths of it disappears in this way. If this is true, the seven-inch layer would be reduced to less than one and one-half inches, and a layer one foot in thickness would require between 8,000 and 9,000 years. The aggregate thickness of coal is frequently as much as 100 feet, and sometimes as much as 250 feet. At the above rate of accumulation, periods ranging from nearly 1,000,000 to nearly 2,500,000 years would be needed for the accumulation of such thicknesses of coal. It should be borne in mind, however, that much depends on the rate of growth of Carboniferous vegetation, which is not known.

On the other hand, these figures refer to the coal only, not to the Coal Measures. The greater part of the Coal Measures is made up of shale and sandstone, and of these formations there are thousands of feet, even where the sediments were largely fine and their accumulation therefore probably slow. It would hardly seem unreasonable to conjecture that their deposition may have consumed an amount of time equal to or even greater than that

demanding by the coal. Doubling the above figures, we get something like 2,000,000 and 5,000,000 years respectively, figures which must be taken to mean nothing more than that the best data now at hand indicate that the Pennsylvanian period was very long.

Close of the period. After the long period of oscillation above and below the critical level recorded by the Coal Measures, the interior east of the Mississippi was brought above the level of the sea, not to sink again beneath it during the Paleozoic era, and some of it at no later time. This emergence marks at once the close of the Carboniferous, and the inauguration of the Permian period. It is also probable that the deformative movements which were to develop the Appalachian Mountains began at this time. There were notable changes also in the western half of the continent, for the Permian system is much less wide-spread than the Carboniferous. Where the Permian occurs, its constitution and its fossils indicate not only different relations of land and water, but different conditions of erosion, and the absence of the sea from some areas where deposition was in progress.

IN FOREIGN COUNTRIES

Europe

As in America, the oldest formation of the Upper Carboniferous in Europe is often a conglomerate and sandstone formation, the *Millstone grit*, which in some parts of Britain attains a great thickness. The Coal Measures of western Europe, like those of eastern North America, consist principally of shales (and clays), with subordinate amounts of sandstone and limestone. Associated with these commoner sorts of rock, there are beds of coal and clay-iron-stone, both of which occupy positions corresponding, in all essential respects, with those of similar formations in eastern North America. There is workable coal in Great Britain, Ireland, Belgium, France, Spain, Germany, Austria, and Russia, but the total area of productive coal in Europe is much less than in America. The number of coal seams is large in many places. Thus in Westphalia the number of workable beds is said to be 90. The aggregate (maximum) thickness of the coal in Lancashire is 150 feet, and in West-

phalia, 274 feet. Here, as elsewhere, beds of marine origin alternate with those which were deposited on land, in marshes, etc.

In Russia, as already noted, the Lower Carboniferous contains most of the coal, while the Upper is made up chiefly of limestone, though in southern Russia (Donetz coal-field) there is coal in the Upper division. The Upper Carboniferous limestone of Russia (*Fusulina limestone*) is represented by similar formations in southern Europe. The faunas of the marine part of the system in Europe have much likeness to those of western North America, suggesting that marine life was able to pass between these continents, via northern Asia.

The upper part of the Upper Carboniferous system of Europe at various points and at various horizons contains boulders, sometimes of large size, and beds of breccia or conglomerate of sub-angular fragments. The boulders are of granite, gneiss, schist, quartzite, etc., and occur both singly and in groups. They have often been thought to represent deposits made by icebergs, and so to point to the existence of glaciers; but this interpretation has not been established. Other interpretations, such as the transportation of the boulders by uprooted and floating trees, are tenable.

North of the European continent, the Carboniferous formations (*Fusulina limestone*, Coral limestone, etc.) are represented in some of the Arctic islands (Spitzbergen, Nova Zemla, Bear Island).

Igneous rocks and crustal disturbances. Igneous rocks are associated with the Upper Carboniferous formations of sedimentary origin in western Europe. Their extrusion seems to have been an accompaniment of the crustal disturbances which began in middle and western Europe at the close of the preceding period, as already noted, and continued through the Permian.

Other continents. The Upper Carboniferous of *Asia* is represented by both marine and non-marine formations. Among the former is a thick limestone, wide-spread in southern China¹ and the Malay Peninsula, overlying the Devonian conformably. The non-marine phase, with numerous beds of coal, is found in Asia Minor, on the east side of the Middle Urals, and in northern and eastern China, reaching to northern Tibet on the one side, and to Mongolia

¹ Researches in China, Carnegie Institution, Willis, Vol. I.

on the other. The Carboniferous of some parts of China has been reported to contain coal-beds of great thickness. The Carboniferous system is also present in India.

The Carboniferous formations of northern Africa correspond in a general way with those of southern Europe. They are generally of marine origin, so far as now known, and without coal, but in southeastern Africa, a coal basin has been reported in Zambesi.¹

The Carboniferous (Permo-Carboniferous) system is well developed in *Australia* where it attains a thickness of 11,000 feet or more. It is partly marine and partly non-marine, and contains coal. The system is remarkable because of its singular conglomerates, some of which are of glacial origin. These will be referred to again in connection with the Permian.

In South America, rocks of Late (Upper) Carboniferous age are somewhat widely distributed, though less so than those of the Devonian period. The system has wide distribution in the lower part of the basin of the Amazon, where it rests on older formations unconformably, and is not generally coal-bearing, but is so in places. In southern Brazil the system contains much coal.²

THE LIFE OF THE PENNSYLVANIAN PERIOD

I. THE PLANT LIFE

With the opening of the Carboniferous period the supreme biological interest shifts from the sea to the land, and centers in the vegetation and in the amphibians.

Plant life was very abundant in the Pennsylvanian period, and the record of it is unusually full and perfect. This completeness has doubtless given the flora of this period an undue prominence over those which preceded it and succeeded; yet it was really a great period in the history of plant life. Angiosperms, the dominant plants to-day, had not yet appeared. Gymnosperms including the so-called "seed-ferns," held an important place. Pteridophytes probably made their greatest display at this time. All the

¹ Kayser, *Geologische Formationskunde*, p. 207.

² White, I. C. *Comissão de Estudos das Minas de Carvão de Pedra da Brazil*, 1908.

great divisions of this group were present, and all of them were nearly or quite at their climax. An attempt is made to represent their general aspect in Fig. 447. Of lower plants, little is known.

The most rapid evolution of floras was perhaps in the Pottsville epoch. Half the genera of that epoch scarcely survived it, and few



Fig. 447.—A composite group of leading Carboniferous plants, adapted from restorations by various paleobotanists, by Mildred Marvin. In the foreground at the right, *Lepidodendron*; at the left *Sigillaria*; in the right center rear, a tree fern, *Cordaites*; in the left center rear, *Cordaites*; at the extreme right and left, *Calamites*.

of them lived after the Allegheny epoch. This was pre-eminently the stage of *Cycadofilices*, *Sphenopteris*, *Neuropteris* and *Alethopteris*, and of the great lycopod types. The early Pennsylvania floras were widely distributed. Thus three floras in Asia Minor may be correlated severally with three floras from the Pottsville

series. The place of origin of the early Pennsylvania floras is not known with certainty, but present evidence points to the land of western Europe and eastern North America, connected by an Arctic land bridge.

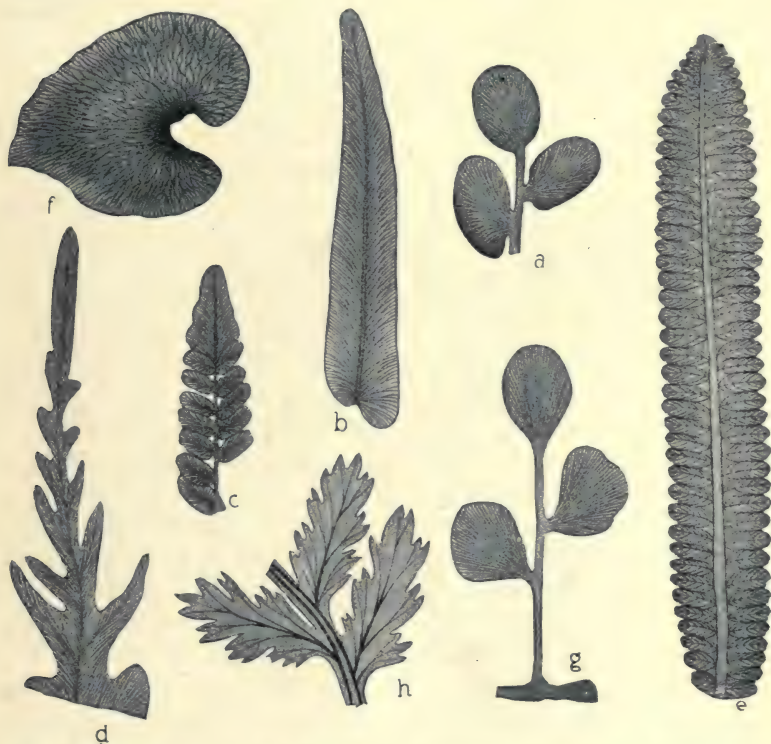


Fig. 448.—A group of fern fronds: *a*, *Neuropteris auriculata*, Brgt.; *b*, *N. angustifolia*, Brgt.; *c*, *N. vermicularis*, Lx.; *d*, *Odontopteris cornuta*, Lx.; *e*, *Pecopteris unita*, Brgt.; *f*, *Dictyopteris rubelia*, Lx.; *g*, *Archæopteris bochsiana*, Goepp.; *h*, *Sphenopteris splendens*, Lx.

The late Pennsylvania floras are not sharply separated from the early ones on our continent, but the distinction is much greater in Europe. The later Pennsylvanian floras indicate, on the whole, less uniformity of climate than the earlier.

The Filicales. Fern-like leaves surpass all other plant fossils in number, but it is now known that most of them belonged to seed-

bearing plants, though ferns were probably present. The ferns are a strangely persistent type. Species still live which, so far as outer form is concerned, might be referred to Carboniferous genera; yet under this general similarity of form, there have been notable changes of structure and function. They seem to have been, even at this early time, thoroughly differentiated from other plants.

The Equisetales (calamites, horsetails). These plants, represented now by a single genus (*Equisetum*), were an important member of the Carboniferous flora. The *calamites* were not only larger, but more highly organized than the modern representatives of this group. The largest tropical forms of to-day have slender stems 30 or 40 feet long, whereas the Carboniferous *calamites* reached a foot or two in diameter and probably 60 to 90 feet in height. They had hollow stems, or a core of pith only, and casts of the interior are common fossils. Branches from the main trunk were comparatively few, and in whorls. The leaves also were in whorls (Fig. 447) and dwarfed, though not so much so as in the modern type, in which the leaves have almost disappeared. The structure of the leaves was of the type adapted to dry weather (xerophytic) as in the pine and in many desert plants, and also, contradictorily enough, as in some undrained swamp plants. The root structure was of the type commonly found under water or in wet mud, and the *calamites* probably frequented swamps and lowlands. The *calamites* were probably associated in thickets and jungles of cane-brake or bamboo type. Their history may run far back, as they were well differentiated in the Devonian. Their ancestry is uncertain, but the next group throws light on their relations.

The Sphenophyllales. Recent studies have shown that the graceful, slender plants with whorled leaves, referred to the genus *Sphenophyllum* (c, Fig. 449), and formerly classed as *calamites*, should be made a class by themselves. Their importance lies chiefly in the fact that while they have certain calamarian features, they have others possessed by the lycopods. This is interpreted to mean that these two groups (calamarians and lycopods, p. 944) were united with the *Sphenophyllales* in a common ancestral form.¹ The stems were long, slender, and apparently weak, and a climbing

¹ Seward, Fossil Plants, p. 413; Scott, Studies in Fossil Botany, p. 494.

habit has been inferred. The leaf structure suggests a shady habitat, perhaps one of undergrowth. The class was represented in the Devonian, had its climax in the middle Pennsylvanian, and continued into the Permian and possibly later.

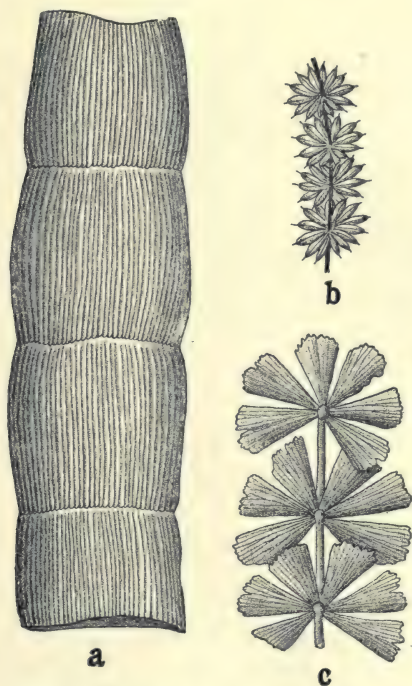


Fig. 449.—Carboniferous Equisetales and Sphenophyllales: *a*, *Calamites cistii*; *b*, *Annularia sphenophylloides*; *c*, *Sphenophyllum longifolium*.

The Lycopodiales. This was the master group of the Coal flora, constituting trees of large size and attaining to the highest organization reached by the pteridophytes. From this high estate, they have since fallen to prostrate or weakly ascending plants of moss-like aspect (club mosses and ground pines). The chief genera were *Lepidodendron* (Fig. 447) and *Sigillaria*, of which the former was the earlier and simpler type. Both take their names from the leaf-scars of leaf-cushions (lepidos=scale, sigilla=seal) which the trunks

retained. In the lepidodendrons the scars are arranged spirally (Fig. 450); in the sigillarians, vertically (Fig. 451).

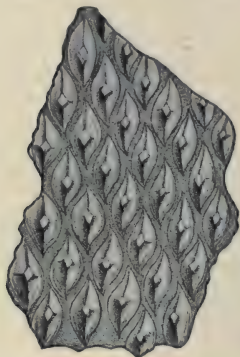


Fig. 450.—Leaf markings of a lepidodendron, *Lycopodites welthermianum* St.

The trunks of *lepidodendrons* were tall, some having been found 100 feet in length. They were erect and branched dichotomously at a great height. The leaves were linear or needle-shaped, ranging up to six or seven inches in length, and set densely on the branches. Some of them were heterosporous, a characteristic pointing in the direction of seeds, but it is not known that seed-producing plants sprang from them. One form of the fruit was distinctly winged, and other forms showed adaptation to transportation by wind.

More than 100 species of lepidodendrons have been described. They seem to have reached their climax early in the period, and nearly all had disappeared by its close.

The *sigillarians* differed from the lepidodendrons in being mostly without branches. They were perhaps the largest of the Carboniferous trees, their trunks reaching six feet in diameter, and 100 feet or more in height. As in lepidodendrons, the stems were densely clothed with erect, rigid, linear leaves. Like the lepidodendrons, they had a thick cork layer, rarely equalled in modern trees, except in the cork-oak and its allies. The sigillarians exceeded the lepidodendrons in abundance before the close of the period, but were on the wane at its close. Perhaps this rather sudden decline, followed by early extinction, was connected with the changes of climate indicated by the Permian glaciation, though this cannot be affirmed.

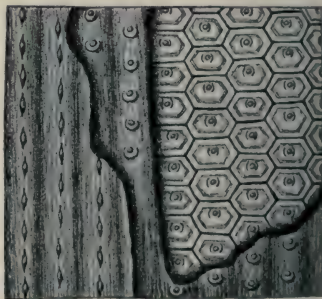


Fig. 451.—Leaf markings of a sigillarian.

The Cycadofilicales. It has been determined recently that many of the fern-like forms possessed structural features which combine the characteristics of ferns and gymnosperms; but since they were seed-bearing, they are classed with the latter. The seeds were borne on leaves, in positions similar to those of the "fruit dots"



Fig. 452.— A typical Cycadofilices, *Lyginodendron oldhamia*. (Restoration by D. H. Scott and J. Allen.)

of ferns. One of the best-known forms is illustrated by Fig. 452, which exhibits the spiny stems and leaves, the highly dissected foliage, the adventitious roots, and shows the general aspect of the type. The structure of their leaves "is altogether comparable to that of a fairly coriaceous fern-leaflet at the present day, and indicates that the conditions to which the structure was adapted could not have been fundamentally different from those which prevail in our own epoch."¹ The limits of the group are not yet known, nor

¹ Scott, *Studies in Fossil Botany*, p. 326.

are its connections with the true ferns. Initial forms have been identified from the Devonian and Lower Carboniferous, and a few are found in the Permian; but the group is essentially Pennsylvanian.

The Cordaitales. This was a remarkable family (now extinct) of gymnosperms (p. 944), having alliances with the "seed-ferns," conifers, and ginkgos, and yet many distinctive features of its own. The Cordaites were tall, rather slender trees, reaching two feet or more in diameter, and 90 feet or more in height. The wood was of the coniferous type, covered, as in so many other plants of the period, by a thick bark. The trunks had a large pith. The leaves were parallel veined, suggestive of monocotyls of the yucca type, and sometimes attained a length of six feet and a width of six inches. They were preserved in great abundance, and make up a large part of some beds of coal. The leaf-structure combined characters now possessed by certain conifers, with others possessed by certain cycads. In one form, the leaf had a distinctly fleshy character, as if adapted to xerophytic life.¹ The floral organs were peculiar to the family, and have been worked out with marvelous success, even the structure of the pollen having been determined. The inflorescence took the form of separate male and female catkins, arranged on slender stalks attached to the stem between the leaves. The seeds (*Cardiocarpus*) were of the cycadian rather than of the coniferous type, and were very abundant and sometimes winged, as if for wind transportation.

It is doubtful whether conifers existed in the Pennsylvanian period, though they were probably represented in the Permian. The upland vegetation is not known, and it is not impossible that conifers, a type especially suited to an upland habitat, prevailed there.

Cycadales have been commonly reported from the Carboniferous, but the evidence remains inconclusive, and the fossils concerned are probably *Bennettitales*, rather than true cycads.

The Coal flora of North America and that of Europe were strikingly similar, implying close geographic relations and like condi-

¹ Scott, op. cit., p. 425.

tions. Nearly all the genera, and about one-third of the species, were identical.

Climatic Implications of the Coal-plants

What suggestions do the Coal-plants give relative to the atmospheric conditions under which they grew? Two partly antagonistic views relative to these conditions have been held. The older one regards the thick deposits of coal as evidence of a very luxuriant growth of vegetation, which in turn has been thought to imply a warm, moist atmosphere, heavily charged with carbon dioxide. The great size of many of the trees, the succulent nature of many of the plants, and the abundance of aërial roots, are appealed to as evidence of mildness of climate, while the absence of rings, and, above all, the great geographic distribution of the floras in relative unity throughout very diverse latitudes, point strongly to equability, an equability which was more pronounced early in the period than toward its close. This view was formerly about the only one, and still predominates, and it is clear that it has much support.

The alternative view which has grown up in recent years postulates less warmth and moisture, and more diversity; in other words, a somewhat nearer approach to the present conditions. It assumes, however, a somewhat higher percentage of carbon dioxide than now, and a climate milder and more uniform than that of to-day. The basis of this view is found in the following considerations: (1). Great thicknesses of coal do not necessarily imply rapid accumulation, any more than great thicknesses of limestone do. Given favorable conditions of preservation, a slow growth will produce great thicknesses. (2). At present the accumulation of peat, the nearest analogue of coal formation, is most favored in cool climates, and is taking place chiefly in high latitudes. (3). The dominant plants of the coal flora had narrow leaves with their breathing pores confined to deep furrows on the under side, devices common to plants of dry regions. (4). The trees had unusually thick corky bark, as though protection from external conditions was needed.

The thickness of the bark, and the form and structure of the

leaves, give a distinctly xerophytic aspect to the overgrowth made up of lepidodendrons, sigillarias, calamites, and cordaites. This is not the case with the undergrowth, but this would not be expected of shaded plants. The force of the inference from the xerophytic aspect of the overgrowth is, however, much weakened by the fact that the vegetation of undrained swamps and bogs assumes many of these xerophytic features. It is clear that a more critical study of the problem is necessary before a final conclusion concerning the climate of the period is reached.

II. THE LAND ANIMALS

Amphibians, insects, spiders, scorpions, and myriapods, lived on the land at this time. The amphibians are perhaps of chief interest, for they were the first of the great line of land vertebrates, the ruling dynasty from that day to this. So far as the evolution of air-breathing vertebrates is concerned, this is one of the most important periods in geological history.¹

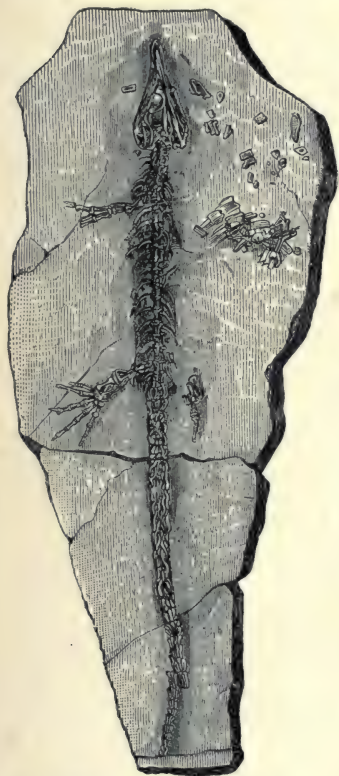
The rise of the amphibians. Tracks attributed to amphibians are found in the Devonian and the Mississippian, but in neither of these systems have any bones of these animals been found in America, and only imperfect ones in Europe. When the fossils of amphibians first appear in abundance, in the later Coal Measures, they were already so differentiated as to imply a long antecedent existence. Most of them were rather primitive in structure, but they were genuine amphibians, not transition forms. In the case of many of them, fossils representing all stages of growth have been found, showing that the young had gills, and that the gills were lost later in life. All of them seem to have had elongate forms of salamandrine aspect, and their heads were well roofed over by the bony plates of the skull. On account of this last feature they are called *stegocephalians* (roof-headed). Some of them have also been named *labyrinthodonts*, from the intricate infolding of the dentine of their teeth. The group varied in length and strength of limb, in agility, ability to climb, etc. The elon-

¹Williston. *The Faunal Relations of the Early Vertebrates*, Jour. Geol., 1909.

gation of their bodies involved a notable multiplication of the vertebræ, one form having no less than 150. In places, their tracks are so abundant as to imply great numbers of individuals, at least locally.

The predominant forms were *branchiosaurs* and *microsaurs*. In size and in habits, the branchiosaurs at least were comparable to the salamanders of to-day. The microsaurs, on the other hand, had made distinct advance, both toward higher types, and away from water, in and about which the branchiosaurs lived. Some of the microsaurs lost their dermal armor, and became fleet, like modern lizards. Before the close of the period, some of them were probably inhabitants of dry lands where fleetness, rather than protective armor, preserved them from their enemies. Differentiation went so far before the close of the period that some of them were limbless and snake-like, crawling reptiles in everything except certain technical details of their palates.

Fig. 453.— Carboniferous amphibian *Lepterpeton dobbsi* Huxley: a microsaurian from Kilkenny, Ireland, about $\frac{2}{3}$ natural size. (Zittel.)



Two other types, *Temnospondyli* (African) and *Stereospondyli*, either persisted from unknown ancestors, or made their advent at this time.

The temnospondylous branch, which reached its highest development in the Permian, is supposed by some paleontologists to be the ancestral line of all modern reptiles, and by others to be the ancestral stock from which mammals arose. The stereospondylous branch, which included the labyrinthodonts, is the only group of Pennsylvanian air-breathing vertebrates which left no descendants.

The labyrinthodonts were doubtless the largest amphibia of the period, some of their skulls reaching a length of half a meter or more.

Not much is known of the food and life-habits of the amphibia, but from their teeth it is inferred that they were predaceous. In Nova Scotia, Dawson took thirteen skeletons representing different species of amphibians from a single sigillarian stump. Since land shells and myriapods are found in stumps with the amphibian skeletons, it has been inferred that some of the amphibians were climbers, and lived on mollusks, myriapods, and similar land life.

The amphibians of different continents were so similar as to suggest great freedom of communication and migration. This free intercontinental migration seems to have come to an end by the close of the Pennsylvanian period.

The marked development of insects.¹ Several hundred species of Carboniferous insects have been identified from the American Coal Measures, and a comparable number from European. They were still, for the most part, of rather primitive types, often uniting characters not now found in the same order. The *orthopters* (cockroaches, *i*, Fig. 454, locusts, crickets, etc.) were greatly in the lead, followed by the *neuropters* (represented by ancestral mayflies). These two orders include about 90 per cent of the known insects. *Hemipters* (bugs), which had appeared earlier, and possibly *coleopters* (beetles) were present, but no fossils of bees, butterflies, or moths have been found, and there is no probability that they existed, since the flowering vegetation on which they depend had not yet appeared. There is also no record of flies. The evolution of insects was therefore one-sided. Curious forms were developed within the orders which lived, and remarkable dimensions were attained, spreads of wing of a foot or more being reported.

Spiders and *myriapods* (Fig. 454) were plentiful. *Scorpions* (*g*) also were present, and several species of *land snails* (*d* and *e*) have been identified. The air-breathing community had become

¹ Scudder, Bull. No. 71, U. S. Geol. Surv., 1891, and works there referred to. Brongniart, *Recherches pour servir à l'histoire des Insectes Fossiles des Temps Primaires*, 1894. Dawson, J. W., *Synopsis of the air-breathing animals of the Paleozoic in Canada up to 1894*.

large and diverse. The amount of carbon dioxide in the atmosphere could not have exceeded that compatible with this life.

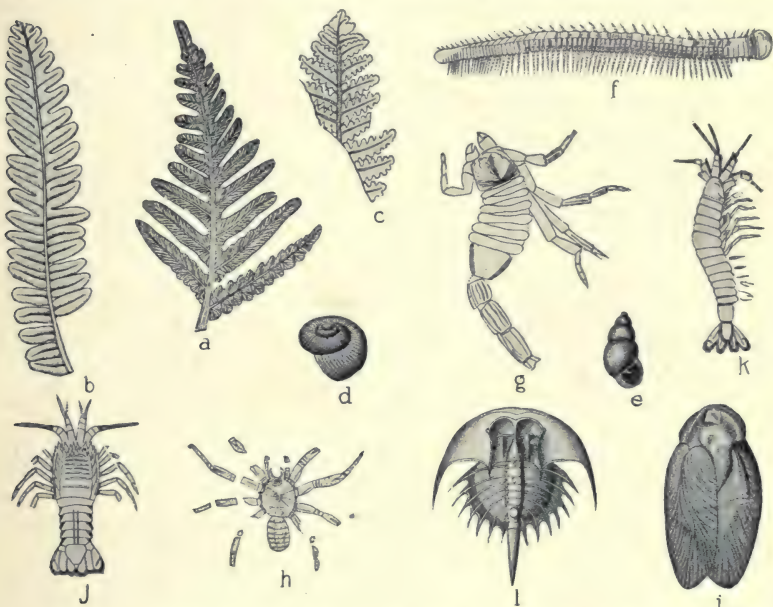


Fig. 454.—*Carboniferous Terrestrial and Fresh-water Life*. Plants: a, *Callipteridium mansfieldi* Lesq., b and c, *Callipteridium membranaceum* Lesq., two species of ferns. Land shells: d, *Zonites priscus* Carp., e, *Pupa vermilionensis* Bradley. These land snails have been referred to genera living at the present time, and although this reference may eventually prove to be incorrect, they are at least close relatives of recent genera. Insects, etc.: f, *Euphoberia armigera* M. and W., a Carboniferous myriapod or thousand-legged worm; g, *Eoscorpius carbonarius* M. and W., a scorpion very similar in type to living forms; h, *Arthrolycosa antiqua* Harger, a spider more primitive than recent forms as seen by the segmentation of the abdomen; i, *Progonoblattina columbiana* Scudd., one of the allies of the modern cockroaches which were the most conspicuous members of the Carboniferous insect fauna. Crustacea: j, *Anthrapalæmon gracilis* M. and W., k, *Palæocaris typus* M. and W., two types of crustaceans found in the Mazon Creek nodules; l, *Prestwichia danæ* M. and W., one of the early allies of the modern horse-shoe crab. (Weller.)

III. THE FRESH-WATER LIFE

Besides fresh-water plants, the life of land waters appears to have consisted of fishes, mollusks, crustaceans, probably of the larval forms of certain amphibious insects, and doubtless of many

unknown forms. Aside from the developments of the fresh-water fish and of the amphibians, perhaps the most suggestive feature was the association of the arthropods with other forms of life.

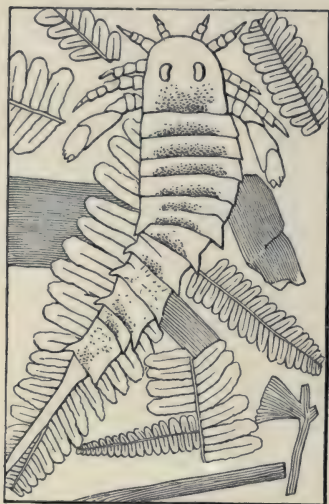


Fig. 455.— Natural association of *Eurypterus mansfieldi* with ferns and calamites. (From Dana, after Hall.)

Eurypterids (Fig. 455) were still in existence, and their relics are so intimately associated with beautifully preserved ferns, calamites, insects, spiders, and scorpions as to leave no reasonable doubt that they were fresh-water forms. There were also crustaceans resembling crayfish, and others of shrimp-like appearance.

IV. THE MARINE LIFE

Because of the approximation of great areas of the continent to sea-level, two phases of sea life had sufficient prevalence to be worthy of note. The first consisted of those forms that habitually occupied the thin edges of the sea, which, in the form of estuaries, lagoons, and shoals, crept in and out on the borders of the continent as the relations of land and sea oscillated, while the second embraced the life of the more open seas. This distinction had doubtless always existed, but it had not before reached equal importance. Life of the first phase was not usually well preserved, but in the coal regions of this period, it constitutes the better part of the record. In this phase, where sandy and muddy flats prevailed, pelecypods and gastropods, together with certain fishes, predominated, while in the more open seas the brachiopods, cephalopods, and the clear-water types were more plentiful.

It is difficult to tell which of the *fishes* should be regarded as marine, which as fresh water, and which as common to salt and

fresh water. It seems clear that much the larger number of those found in the American Coal Measures lived in fresh water; whether also in salt water is uncertain. It is probable that the sharks armed with shell-crushing teeth were chiefly marine, and those with cutting teeth largely so. During the period, there was progress among the fishes in adaptation to swift movement, and in shapeliness of form.

The invertebrates. By comparing the *pelecypods* represented in Fig. 456, with earlier forms, it will be noted that this group had assumed a more modern aspect. The period was doubtless favorable to their advance, by presenting an extensive but shifting habitat that both invited and forced adaptive change. The *gastropods*, on the other hand show less departure from earlier types. They are still distinctly Paleozoic. Ancient and relatively modern types of *cephalopods* lived together, the former represented by straight, plain, small orthoceratites (z, Fig. 456) that might well belong to the earliest Paleozoic period, and the latter by closely coiled goniatites (zz) with curved sutures that might well be early Mesozoic types. The orthoceratites were about to take their final leave, and the goniatites were about to evolve into ammonites, the dominant type of the Mesozoic era.

The *brachiopods* held an important place, and their general facies was like that of the later Mississippian. Some species range not only through northern America and Eurasia, but into the Orient and Australasia. *Crinoids* were a smaller element of the fauna than might have been expected from their previous and subsequent history. There was a close relation between several American and Russian crinoids, implying intermigration. The *cystoids* and *blastoids* were gone. No *starfishes* have been recognized, though they were doubtless present, and *sea-urchins* were rare. *Trilobites*, which commanded foremost attention at the opening of the Paleozoic, are now almost at the point of disappearance. The last representative of the group had the chaste beauty of its early ancestors. *Bryozoans* were not uncommon, but the peculiar devices for support illustrated in *Archimedes* and *Lyropora* of the preceding period were abandoned. *Protozoans* were repre-



Fig. 456.—*Pennsylvanian Marine Fauna*: a, *Eupachyrcrinus magister* M. and G., a crinoid with biserial arms; b, *Fusulina secalicus* Say, a foraminifer shell that sometimes makes up considerable beds of limestone. c-p, brachiopoda: c, *Productus nebrascensis* Owen; d, *Productus costatus* Sow.; e, *Seminula argentea* (Shep.), a spire-bearing common Carboniferous species; f, *Lingula unbonata* Cox, a representative of a genus which persisted from the Cambrian to recent times; g, *Hustedia mormoni* (Marc.); h, *Spirifer cameratus* Mort., a characteristic member of the Pennsylvanian fauna; i, *Productus symmetricus* McCh.; j, *Derbyia crassa* (M. and H.); k, *Enteleles hemiplicata* (Hall); l, *Pugnax uta* (Marc.); m, *Dielasma bovidens* (Mort.); n, *Meekella striatocostata* (Cox); o, *Chonetes granulifera* Owen; p, *Spiriferina kentuckiensis* (Shum.). q-t, pelecypods: q, *Monopteria longispina* Cox; r, *Allorisma subcuniata* M. and H.; s, *Myalina recurvirostris* M. and W.; t, *Ariculopecten occidentalis* Shum. u-x, gastropods: u, *Worthenia tabulata* (Con.); v, *Meekospira peracuta* (M. and W.); w, *Bellerophon percarinatus* Con.; x, *Naticopsis altonensis* McCh. y, z, and zz, cephalopods: y, *Temnocheilus forbesianus* (McCh.); z, *Orthoceras cribrosum* Gein.; zz, *Paralegoceras newsomi* Smith; xx, *Phillipsia major* Shum., almost the last of the trilobites.

sented widely by a little foraminiferal shell (*Fusulina secalicus*, b, Fig. 456), which had about the size and form of a grain of wheat. Their abundance gives character to the *Fusulina* limestone which occurs in America, Europe, and Asia. *Corals* were rare, as might be expected under the environmental conditions of the time.

Map work. No reference to map work has been made since that at the close of the chapter on the Ordovician, p. 535. Experience has shown that if the principles of stratigraphy as illustrated by the Cambrian system, are well developed as suggested on p. 506, further map work may be deferred to about this point. Many of the maps available for this work involve most of the Paleozoic systems of rock, and if map work on these systems is taken up at this point, it may be made to serve as a review of the history of the periods when these systems were deposited.

The following folios of the U. S. Geological Survey are among those especially serviceable in this connection: *Arizona*, Clifton, Globe; *Arkansas-Missouri*, Fayetteville; *Arkansas-Oklahoma*, Winslow; *California*, Colfax, Nevada City Special, Redding; *Colorado*, Needle Mountains, Walsenburg; *Illinois-Indiana*, Danville; *Indiana-Illinois*, Patoka; *Kansas*, Independence; *Massachusetts*, Holyoke; *Missouri*, Joplin; *Montana*, Livingston; *New Jersey*, Franklin Furnace; *New York*, New York City; *Oklahoma*, Atoka, Tishomingo; *Pennsylvania*, Ebensburg, Elkland-Tioga; *Tennessee*, Briceville, Kingston, Standingstone; *Tennessee-Georgia*, Ringgold; *Utah*, Tintic; *Virginia-Tennessee*, Bristol; *Virginia-West Virginia*, Monterey; *Washington*, Snoqualmie; *West Virginia*, Charleston; *Wisconsin*, Lancaster-Mineral Point; *Wyoming*, Alladin, Cloud Peak-Fort McKinney, Sundance.

If a fuller list is desired, the following may be added: *Arizona*, Bisbee; *Colorado*, Ouray, Rico; *Illinois*, Chicago; *Maine*, Penobscot Bay, Rockland; *New Jersey*, Passaic; *Oklahoma*, Muscogee, Talequah; *Tennessee*, Chattanooga; *Wisconsin*, Milwaukee; *Wyoming*, Absaroka (Crandall Sheet), Bald Mountain-Dayton, Yellowstone. If the full set of folios is available, folios even more suitable for special localities may be selected.

CHAPTER XXII

THE PERMIAN PERIOD

FORMATIONS AND PHYSICAL HISTORY

At the close of the Pennsylvanian period much of the central and eastern parts of the United States became dry land, and the sea-covered area in the west was greatly restricted. The area of land was perhaps as large as at any time since the beginning of the Paleozoic. The waters which still lay upon the continent were partly in the form of lakes and inland seas, and partly connected with the open ocean, but the areas which the sea overspread at the beginning of the period were largely abandoned before its close. These changes in geography reflected themselves both in the distribution of the Permian formations and in their character.

East of the Mississippi. Fresh-water sedimentation continued much as before during the earlier part of the period in some parts of the east (parts of Pennsylvania, West Virginia, Maryland, and Ohio), and with the other formations there is some coal. The Appalachian belt farther south seems not to have been the site of deposition. In Nova Scotia, New Brunswick, and Prince Edward Island, non-marine Permian strata rest on Carboniferous beds in such a way as to show that sedimentation was not seriously interrupted, and the two systems are separated on the basis of fossils, as in the eastern part of the United States.

West of the Mississippi. The system is better developed west of the Mississippi than east of it. It is best known in Texas, Kansas, and Nebraska, where it is partly marine and partly non-marine.

In Kansas and Nebraska the lower part of the Permian is marine, and though the connection has not been traced, the Permian of these states is probably continued northwestward to Wyoming and South Dakota, for marine Permian beds in the Laramie Mountains and the Black Hills have fossils very similar to those of Kan-

sas.¹ The marine Permian of Kansas is overlain by beds containing gypsum and salt, and possessing other features which show that the open sea of the region was succeeded by dissevered remnants, or by salt lakes whose supply of fresh water was exceeded by evaporation. With the saline and gypsiferous deposits and above them are the "Red Beds" formerly referred to the Trias; but most of them are now classed as Permian, as are most (though not all) of the Red Beds east of the mountains. Some of the Red Beds in western Texas, New Mexico, and elsewhere are perhaps later than Permian, and some in Oklahoma, Kansas, Colorado,² and perhaps elsewhere, are probably older.

In the Staked Plains of Texas the system has its greatest development. The oldest part (*Wichita formation*) indicates that the critical attitude which characterized the surface farther east during the Pennsylvanian period, now affected Texas, for the beds are partly of marine and partly of fresh-water origin. These beds are succeeded by a formation of limestone (the *Clear Fork*) of marine origin, which overlaps the Lower Permian. The Upper Permian (*Double Mountain formation*) which follows, indicates a reversal of relations, for much of Texas was again cut off from the ocean, and converted into an inland sea, or into inland seas, in which the phases of deposition common to such bodies of water took place. Occasional beds of limestone with marine fossils point to occasional incursions of the sea, while deposits of salt and gypsum point with equal clearness to its absence, or to restricted connections, and to aridity of climate.³

Throughout much of the area west of the Rocky Mountains, the Permian has not generally been differentiated. There is often conformity between the Carboniferous below and the beds classed as Trias above, suggesting the presence of unseparated Permian between. In northern Arizona, however, and in southwestern

¹ For an account of the Permian of this region, see Prosser, *Geol. Surv. of Kansas*, Vol. II, 1897, pp. 55-97; Knight, *Jour. Geol.*, Vol. VII, pp. 35-74, and Bull. 45, Wyo. Experiment Station, and *Jour. Geol.*, Vol. X, pp. 413-422; Barbour, *Nebraska Geol. Surv.*, Vol. I, p. 129, and Darton, 19th Ann. Rept., U. S. Geol. Surv., Pt. IV.

² Cross, *Jour. Geol.*, Vol. XV, p. 633.

³ For Permian of Texas, see Cummins, *Geol. Surv. of Texas*, 2d Ann. Rept., pp. 394-424. *Ibid.*, 4th Ann. Rept., 212-232.

Colorado and perhaps at other points, there is an unconformity at the top of the Permian.¹ The presence of Permian in New Mexico,² northern Arizona³ and the Wasatch Mountains, suggests that the Permian sea perhaps extended west from Texas as far as the Great Basin for a part of the period; but if so, the continuity of the beds has since been interrupted by erosion. A very considerable thickness of marine Permian (3,800 feet) is reported from Utah.⁴ The Permian deposits of the far west, as well as some of those in the longitude of Texas and Kansas are often red. This color so often characterizes formations known to have been made in inclosed basins, that the connection can hardly be fortuitous.

Thickness. In the Appalachian region, the Lower Permian beds, sandstone and shale with thin seams of coal, have a thickness of about 1,000 feet. The Upper Permian is wanting. In Kansas the thickness is twice as great, while in Texas it reaches 7,000 feet.

Correlation. In the region east of the Mississippi, the Permian is so closely associated with the Coal Measures that the two were formerly classed together. Were this region only considered, this classification would appear to be satisfactory. In the western part of the continent, on the other hand, the separation of the Permian from the Carboniferous will probably prove to be more distinct, when details have been worked out, and its relation with the Trias close. The Permian period is best looked upon as a transition period from the Carboniferous to the Trias, and so from the Paleozoic to the Mesozoic. Its close relationship to the underlying system in some places, and to the overlying system in others, is therefore to be expected.

THE FOREIGN PERMIAN

Europe

In Europe, as in America, the Carboniferous period was brought to a close by very considerable changes, for much of the area which

¹ Cross, and Cross and Howe, Bull. G. S. A., XVI, 447; Silverton Folio, U. S. Geol. Surv., and Jour. of Geol., Vol. XV, p. 634.

² Herrick, Jour. Geol., Vol. VIII, pp. 112-125; and Am. Geol., Vol. XXXI, p. 76.

³ Walcott, Am. Jour. Sci., Vol. XX, 1880, p. 221.

⁴ Boutwell, Jour. Geol. XV, p. 434.

had been receiving deposits during that period was exposed to erosion at its close. Subsequently, through further changes, much of the same surface was again brought into a position for renewed deposition, partly from fresh and partly from salt waters. The Permian system is on the whole much more distinct from the Carboniferous, than the Permian of the eastern part of North America is from the Pennsylvanian.

The Permian of Europe has two somewhat different phases known as the *Dyas* and the *Permian* respectively. The former name had its origin in the twofold division of the system, characteristic of western Europe, and the latter came from a province of Russia where the formation is well developed. Except in Russia, its extent at the surface is not great.

The Dyas Phase

Lower Permian. Where the Dyas phase of the formation is developed, as generally in western and central Europe, the Lower Permian (*Rothliegende*) consists of a series of fragmental beds made up of shale, sandstone, conglomerate and breccia, and a large amount of igneous rock, in the form of lava-sheets, dikes, and pyroclastic material.

The character of the formations and of their fossils is such as to show that much of the sediment was accumulated in inland seas, and in salt and fresh lakes. Gypsum, salt, and a meager fauna of dwarfed and stunted species, some of which are marine, are among the distinctive marks of the series. But the sea sometimes had access to the inland areas of sedimentation, as some of the fossils show. The shallow-water or subaërial origin of much of the Permian is shown by the sun-cracks, rain-pittings, ripple-marks, tracks of terrestrial and amphibious animals, etc. In keeping with the conditions of its origin the *Rothliegende* in various parts of Europe contains coal.

Especial interest attaches to the conglomerates and breccia of the system because of their likeness to glacial drift.¹ This like-

¹ Ramsay, Q. J. G. S., 1855; and Geikie, op. cit., p. 1064. There seems to be some question as to whether these formations should be referred to the Carboniferous or the Permian.

ness is found not only in the presence of large boulders, but in their character and in the matrix in which they are set. Furthermore, the stones have now and then been observed (Midlands and west England) to carry marks which have been thought to be glacial striæ. This origin of the marks, however, has been called into



Fig. 457.— Sketch map of Europe during the later part of the Permian period. The lines indicate areas of marine deposition, the broken lines, areas of lagoon deposits; and the dots, areas of continental (land) deposition. (After De Lapparent.)

question. The conglomerate is wide-spread, and in some cases contains boulders which have been transported considerable distances.

The Upper Permian. The Upper Permian of western and central Europe (the Zechstein of Germany) is unlike the Lower in several important respects. It contains much more limestone and dolomite, but neither coal, igneous rock, nor, except at its very base,

conglomerate. From the stunted aspect of the fossils, and from the association of the dolomite with gypsum, salt, etc., it has been thought that the limestone and dolomite may be largely chemical precipitates. Some parts of the Permian are, however, of marine origin.

The Upper Permian of central and western Europe contains the thickest salt-beds known in any part of the earth. Near Berlin, one of these salt-beds has been penetrated about 4,000 feet, and its bottom has not been reached. In addition to common salt, salts of potash and magnesium were locally (Strassfurt) deposited in such quantity as to be commercially valuable. The world's supply of potassium salts, with the exception of saltpetre, comes from these beds. Like rock salt, these salts probably represent precipitates from waters of enclosed basins under special conditions.

The Permian Phase

The typical Permian phase of the system underlies the larger part of Russia (in Europe), and appears at the surface over a large area in the southeastern part of that country. It is generally conformable on the underlying Carboniferous, and is partly marine and partly non-marine. It contains salt, gypsum, etc., and also, in some horizons, marine fossils.

In southern Europe the Permian is of marine origin, for the most part, and is generally conformable on the Carboniferous.

Summary. Great areas in both Europe and North America seem to have maintained a halting attitude near the critical level during much of the period, while in both continents there were considerable areas of dry land. In both continents there are beds which accumulated in fresh water, in salt lakes or inland seas, and on the floor of the epicontinental seas. But the differences between the continents are not less instructive than the likenesses. In Europe the Permian period was distinguished by great igneous activity, while in America activity of this sort is unknown. The Permian of Europe seems to be more closely allied, stratigraphically, with the Trias than with the Carboniferous, and while the same is perhaps true of the western part of North America, the opposite is true for the eastern part.

*Other Continents*¹

In other parts of the world the Permian is widely developed. In countries about the Indian Ocean, including South Asia, Australia, and South Africa, there is usually a less distinct break between the Carboniferous and Triassic systems than in Europe, and locally at least, the Permian seems to bridge the interval.

Permian glacial formations. The most remarkable fact about the Permian system outside of North America and Europe is that it includes formations of *glacial origin*, and that these occur down to and even slightly within the tropics. Such formations are found in Australia, Asia, Africa, and South America, all the continents which have large areas in low latitudes.

In *Australia* the Permian formations of glacial drift (locally nine or ten of them) are interbedded with marine formations, the aggregate thickness of the whole being not less than 2,000 feet. Not less than 30 or 40 beds of coal are included in the system. The recurrence of the boulder beds points to the repeated recurrence of glacial conditions, and the great thickness both of elastic beds and of the included coal point to the great duration of the period through which the several glacial epochs were distributed.

Counting Tasmania, where glacial deposits are also found, the glaciation of Australia had a known range of nearly 22° in latitude, and about 35° in longitude, though it is perhaps not probable that all the area within these limits was glaciated. The glacial phenomena are known chiefly at low levels, descending in some places nearly to the sea. Not only is the altitude of the region low now, but it was probably low during glaciation, as shown by the relation of the glacial deposits to the marine beds. Whatever the difficulties in the way of its explanation, the fact of a long period during which glacial conditions recurred many times, must be accepted.

The marine beds associated with the glacial deposits seem to match approximately those of the Carboniferous period elsewhere, but the plants of the associated coal have the general facies of the Triassic flora. Permian fish remains are found above all the boulder

¹Q. J. G. S., Vol. LII, 1896, p. 289; Am. Geol., Vol. XIII, 1889, p. 299; and Scot. Geog. Mag., Vol. XVII, 1901, p. 57.

beds, suggesting that the glacial conditions were over before the end of the Permian. The testimony of the plant fossils is therefore that the period of glaciation was late Permian or early Triassic; that of the marine fossils that it was late Carboniferous or early Permian.

In *India*, too, there are glacial formations (*Talchir conglomerate*) of about the same age, with fossil plants like those of Australia, in associated beds. The bed on which the glacial formations rest is in some places striated and roche-moutonnée, as beneath modern glacial deposits. These formations are in some respects even more remarkable than those of Australia, for they reach below latitude 18° , and are, therefore, several degrees within the Tropic of Cancer; not only this, but they occur at low levels, descending in places nearly to the level of the sea. Similar formations, believed to be of the same age, appear in the Salt Range of India (Lat. 32°), in the central Himalayas, in Cashmere, and Afghanistan. In the Salt Range, a marine Permian formation overlies the glacial series.

In *South Africa* many of the boulders of the glacial beds (*Dwyka conglomerate*) are striated, and the bed on which the glacial conglomerate rests shows indisputable marks of ice action in many places. The glacial beds are believed to have extended as far north as $26^{\circ} 40'$ in the Transvaal. Glacial conglomerates are also present in *South America* in the southern part of Brazil. The associated coal formations carry the same flora (*glossopteris flora*) as in the other continents.

The known Permo-Carboniferous glaciation of Australia, India, Africa, and South America, is found in two zones, the one north and the other south of the equator. In neither zone have the limits of glaciation been accurately determined; but in the former it is known to have extended from latitude 18° to about 35° , and probably still farther north, while in the latter it is known to have extended from latitude 21° to 35° . In an equatorial zone about 40° in width, glaciation has not been discovered. The glaciation can hardly be said to be limited in longitude. Glacial conditions must, therefore, have prevailed about the borders of an area many times as large as that covered by ice in the northern hemisphere during the Pleistocene glacial period.

The marked likeness of the floras associated with the glacial deposits throughout these four continents is believed to be evidence that there was land connection between them at the time of the glaciation. The age of these glacial beds is not absolutely established; for the Carboniferous and Permian are not clearly differentiated in the regions where the glacial formations occur. Perhaps the best judgment that can be formed now is that the Paleozoic glaciation culminated in the early part of the Permian period.

CLOSE OF THE PALEOZOIC ERA

The close of the Paleozoic era was marked by much more considerable geographic changes than the close of any period since the Proterozoic, though they may be said to have been in progress during the Permian period, rather than to have occurred at its close.

The more important geographic changes in North America which were far advanced by the close of the Paleozoic, were (1) the development of the Appalachian mountain system at the western border of Appalachia; (2) the deformation of the surface of Appalachia; (3) the development of the Ouachita Mountains; (4) the final conversion of the larger part of the area between the Great Plains and Appalachia from an area of deposition to an area of erosion; and (5) the restriction at the west of the area of sedimentation in the western interior.

Such extensive geographic changes, involving the conversion of extensive areas from sea bottom into land, must have caused profound changes in the circulation of ocean waters, in the climate of many localities, and in the distribution of terrestrial and marine life.

THE LIFE OF THE PERMIAN

The life of the Permian must be interpreted in connection with the extraordinary physical conditions which formed its environment. Between them and the life there must have been reactions and adaptations of the utmost significance, if we could surely read them. At no period save our own were the phenomena so pronounced, and hence, with little doubt, so rich in possible instruction as to the adaptation of life to extreme conditions.

The salient facts in connection with the physical conditions of the Permian were *glaciation* and *aridity*. In view of these facts, certain questions relative to the life arise: (1) Did it possess such powers of adaptation as to meet its extraordinary environment by adjusting itself to it? (2) Was it destroyed co-extensively with the changes in environment? (3) Did it elude adverse conditions by migrating from one area to another as the adverse conditions shifted (hypothetically)? (4) Did its composite experience embrace all these alternatives, and if so, what measure of each?

The impoverishment of life. In the early days of geology it was commonly held that a complete destruction of all things living on the face of the earth attended the close of the Paleozoic era, and that a re-creation followed; for in the state of knowledge of that time, no Paleozoic species was known to have lived on into the following era. Had it been known that glaciation pressed upon the borders of the tropics from either side, and that aridity prevailed over large areas elsewhere, it would have added great strength to the conviction of a universal catastrophe to life. It is now known that some species bridged the interval, and it is believed that others underwent modifications which enabled them to live. The progress of investigation is bringing more and more evidence of this kind to light, and reducing the disastrous implications of the record. Not only this, but the compensating effects of the strenuous conditions in calling into play the powers of adaptation and resistance of the organisms are coming to be recognized. Notwithstanding all this, it appears that the life of the period was greatly impoverished. A census made not many years ago gave the known animal species of the Carboniferous period as 10,000, while those of the Permian period were only 300. A census to-day would probably increase the Permian ratio, but the contrast would still be great.

I. *The Plant Life*

The change of the vegetation from the Carboniferous to the Permian was rather marked in America, though not, at the outset, radical. Of the 107 species of plants recorded from the lowest beds referred to the Permian in West Virginia and Pennsylvania, 22 are found in the Coal Measures below, and 28 in the Permian

of Europe. This and other similar facts show that a rather profound change was in progress, but that it was not abrupt.

Only a small part of the total floral changes of the Permian appears in the American record, as now known; but the nature of the early change is distinctly indicated. The *Lepidodendrons* disappeared, the *Sigillaria* became rare, and the *Calamites* were greatly reduced in importance. The general features of the fern group remained much as in the preceding period, but most of the species and many of the genera were new. The *Cordaites* continued,

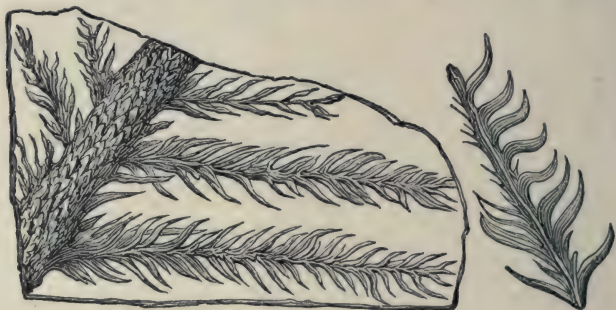


Fig. 458.— *Walchia piniformis*, a Permian conifer of Europe.

and initial forms of *ginkgos* appeared, giving to the flora a Mesozoic cast.

In Europe the residual Carboniferous species declined as the period advanced, and the general aspect of the flora was that of poverty. Two new types of much interest came in and became characteristic. One of them (*Walchia*, Fig. 458), probably a conifer, resembled an Araucarian conifer in its foliage, though its seed organs were apparently different. The second type (*Voltzia*, *h*, Fig. 459) is a supposed forerunner of the group to which the giant sequoia and the bald cypress belong. Both these types had a pauperitic aspect.

The *Glossopteris* flora. The most remarkable vegetal event of the period was the evolution of the *Glossopteris* (tongue-fern) flora in the southern hemisphere, and its migration into the northern. Many features of this flora give support to the view that it was evolved to meet the adversities of climate in and about the glaciated

regions. Developed thus amid adverse surroundings, if not under adverse conditions, the flora not only took on a resistant aspect, in simple outlines and compact forms, but soon gave evidence of its



Fig. 459.—Representative types of the Glossopteris Flora. *a*, *Glossopteris communis*, Fstm.; *b*, *G. angustifolia*, Bgt.; *c*, *Gangamopteris cyclopteroides*, Fstm.; *d*, *Noeggerathiopsis hislop*, Bunb.; *e*, *Neuropteris valida*, Fstm.; *f*, *Schizoneura gondwanensis*, Fstm.; *g*, *Phyllothea indica*, Bunb.; *h*, *Voltzia heterophylla*, Bgt.

vitality by spreading northward into east Africa and Asia, and then Europe. It reached northern Russia in the later part of the Permian period, and was there associated with forms typical of the European Permian flora. It is also found in Brazil and Argentina.¹

¹ In Brazil, this flora, closely allied to that of the Talchir-Karharbari series of India, is found in the coal-bearing formations. I. C. White and David White, *Comissão da Custódia das Minas de Carvão de Pedra do Brasil*, 1908.

Its vitality is further shown in that its descendants became a dominant feature in the Mesozoic floras that followed.

II. *The Land Animals*

The Amphibians. The amphibians which reached their climax in the later portion of the Pennsylvanian period, were still abundant in the early Permian, but before the end of the period, they were overshadowed by the rise of the reptiles, which were without doubt their descendants. The Permian amphibians were much like those of the preceding period, but showed some advance in organization, and some reptilian tendencies. The amphibians of this period included the earliest known type of modern amphibians (*Lysorophus*), so far as now known, peculiar to the North American Permian.

Primitive reptiles.¹ While the reptiles probably began to differentiate from amphibians earlier, the oldest certain relics of reptiles go back but little beyond the beginning of the Permian. Before the close of the period the group was large and complex. At least three distinct phyla are known to have existed. One of them (*Pelycosaurus*), pronouncedly reptilian in character, had branched off before the close of the Pennsylvanian period. Another (*Cotylosaurus*) had a singular development of dermal carapace, strongly suggestive of turtles, and unknown outside of North America. The third phylum included small, crawling reptiles, with large heads, short tails, powerful and short limbs, whose nearest and yet rather remote relatives (*pareiasaurus*) are found in South Africa. The American forms were probably derived from the same stock as their African allies, but the types in the two continents had, as a result of long isolation, become somewhat distinct. The origin of the branch of the reptiles which gave rise to the mammals, was probably in Africa.

Some of the reptiles possessed peculiar interest because of the mammalian aspect of their skulls, their teeth, and some other parts of their skeletons (Fig. 460). These were especially abundant

¹ Williston, The Faunal Relations of the Early Vertebrates, Jour. Geol., Vol. XVII, 1909.

in South Africa (Karoo beds¹), but they have been found also in Europe.

The rapid and diverse deployment of the early reptiles in a period of general life-impoverishment is not a little remarkable, but as the reptiles were air-breathers, the key to their rise may lie in a more oxygenated atmosphere, a point to which we shall return.



Fig. 460.—*Palæohatteria longicaudata*, a primitive diapsidan of the order Protorosauria, about $\frac{1}{4}$ natural size. (Restoration by J. H. McGregor.)

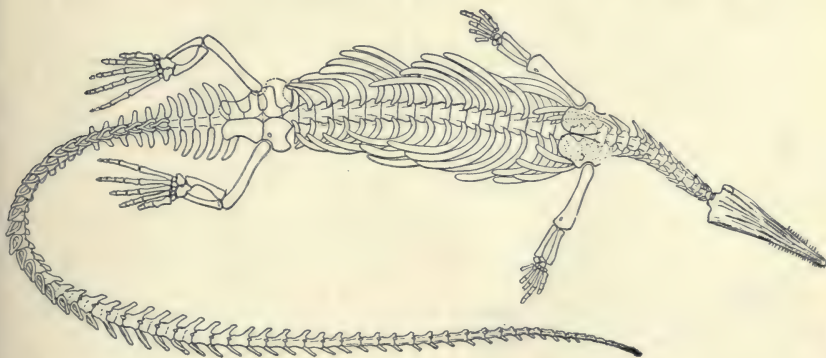


Fig. 461.—*Stereosternum tumidum*, from Brazil, about $\frac{1}{4}$ natural size. (Restoration by McGregor.)

The Permian of Texas and Oklahoma affords the richest Permian vertebrate fauna now known. In contrast with the vertebrate fauna of the Pennsylvanian system, the Permian vertebrate fauna of North America is so unlike the corresponding faunas of other continents as to imply the absence of migration of land animals between North America and other continents. This isola-

¹The Karoo beds, so wonderfully rich in significant vertebrate remains, are regarded as Permian in part, and Triassic in part. Broom, *Geol. of Cape Colony*, 1905, pp. 228-249.

tion seems to have lasted from the later part of the preceding period, until well into the Triassic.

The Permian record of the arthropods and of the terrestrial mollusks is very poor, and probably represents an impoverished state of these classes, but local exceptions will doubtless yet be discovered.

III. *The Fresh-water Life*

The amphibians and some of the reptiles constituted, in a sense, a portion of the fresh-water as well as the land life. Besides these, fishes were abundant, locally at least. On the whole they had a rather modern aspect.

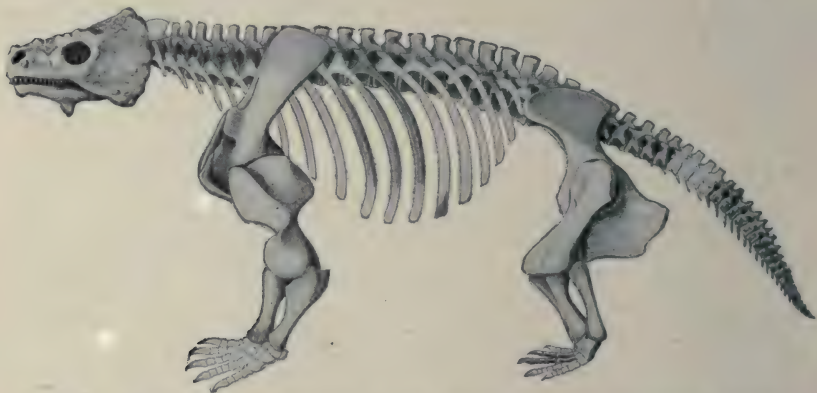


Fig. 462.—*Pareiasaurus serridens*, Karoo formation, Cape Colony, S. Africa; $\times$ about 1-25. (After Broom.)

There were fresh-water mollusks, some of which resembled unios. The arthropods, so far as known, show but little change from those of the preceding period.

IV. *The Marine Fauna*

The withdrawal of the epicontinental seas from considerable portions of the continents reduced the territory available for shallow-water sea life, and of such life there was a great reduction. It is to be noted that this reduction came at a time when conditions were unfavorable for land life (p. 669). In North America the restricted marine fauna lived in tracts just previously occupied by the ex-

panded seas of the Pennsylvanian period, and the Permian faunas were lineal descendants of predecessors occupying the same area. At first, nearly all the species were the same as those of the preceding period, and hence difficulty has always been experienced in

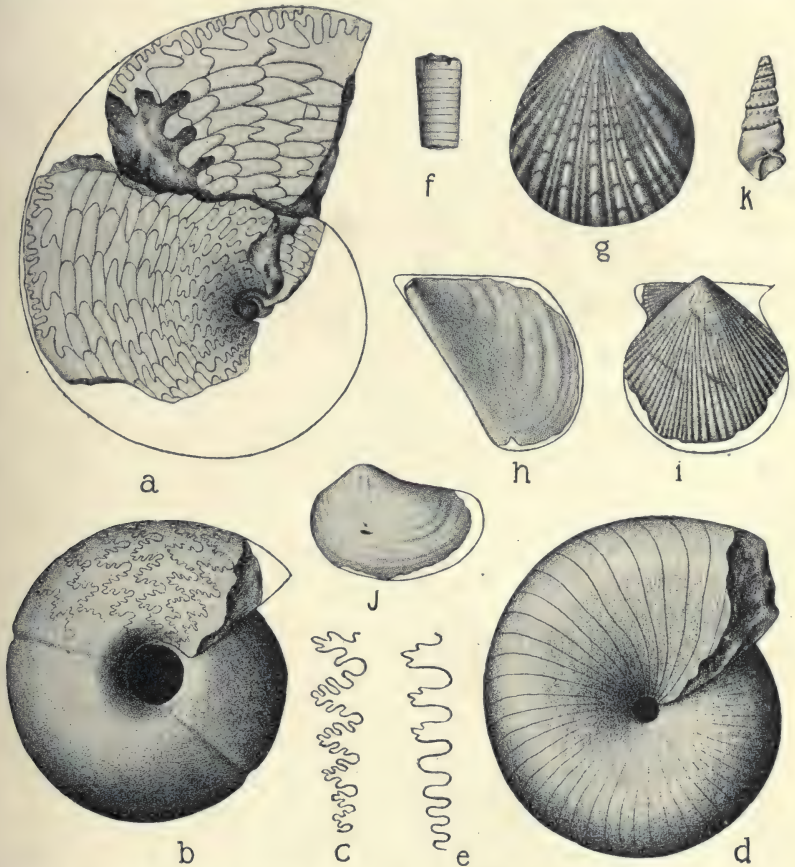


Fig. 463.— *Marine Permian Fauna*. *a-f*, *Cephalopods*: *a*, *Medlicottia copei* White; *b* and *c*, *Waagenoceras cumminsi* White; *d* and *e*, *Popanoceras walcotti* White, three forms of ammonoids with sutures more complicated than in earlier forms; *f*, *Orthoceras rushensis* McCh., one of the last of the orthoceratites. *g-j*, *Pelecypods*: *g*, *Pseudomonotis hawni* (M. and W.); *h*, *Myalina permiana* (Swall.); *i*, *Aviculopecten occidentalis* (Shum.); *j*, *Sedgwickia topekaensis* (Shum.). *k*, *Murchisonia* sp., a gastropod.

drawing a dividing line between them. The known species of the Permian of the Great Plains are only about 70, and of these about one-half are *pelecypods*. Among the *brachiopods*, the productids were the most characteristic forms. This system records the last flourishing stage of the productids, the orthids, the spirifers, and the arthyrids, types which had a long history.

The increasing complexity of the sutures of the coiled *cephalopods* has been noted in previous chapters. In the later part of the Permian, the complexity became still greater (Fig. 463), foreshadowing the intricacy of the Mesozoic ammonites; but older types (goniatites and nautiloids) mingled with the new. Interestingly enough, there was also the ancient straight form (*Orthoceras*, *f*, Fig. 463), in the last stage of its prolonged career. The contrast (compare *a*, Fig. 463) between the disappearing straight type, in its depauperate form, and the robust youthful ammonites, about to become a ruling dynasty, is marked.

The retreatal tracts of the marine life. As in previous transition epochs when epicontinental waters were largely withdrawn, the marine faunas found special refuge in certain embayments or border tracts which, in connection with the coastal belts, permitted them to re-form themselves, regenerate their species, and prepare for a succeeding invasion of the continental areas. On the American continent, the St. Lawrence embayment had done repeated duty in this line; but there is no specific evidence that it participated notably in the Permo-Triassic transition. The border of the Gulf of Mexico, the Mediterranean tract, notably in the region of Sicily and southeast Europe, and the Ganges-Indus tract of southern Asia, seem to have been special areas of refuge and regeneration. Here and on the continental borders generally, the shallow-water marine faunas passed from the Paleozoic to the Mesozoic phases. The restriction, compared with the expansional stage of the Mississippian period, was great; but the faunas emerged with new species born in adversity, ready for conquest when the re-advancing seas should give them an expanding realm. Unfortunately, the sediments in which this transition of faunas should be recorded, are, for the most part, buried and inaccessible.

THE PROBLEMS OF THE PERMIAN

Between the marvelous deployment of glaciation, a strangely dispersed deposition of salt and gypsum, an extraordinary development of red beds, a decided change in terrestrial vegetation, a great depletion of marine life, a remarkable shifting of geographic outlines, and a pronounced stage of crustal folding, the events of the Permian period constitute a climacteric combination. Each of these phenomena brings its own unsolved questions, while their combination presents a series of problems of great difficulty. More than any other period since the Cambrian, the Permian is the period of problems. These marked phenomena were probably related to one another, and their explanation is quite sure to be found in a common group of co-operative factors. While it is too much to hope for a full explanation at once, there is no occasion to blink the facts or evade the issues they raise.

It is to be noted that none of the factors in this combination were wholly new to geological history. There had been glaciations almost as strange in early Cambrian or pre-Cambrian times (Norway, China, Australia), and perhaps in the Devonian (South Africa); there had been signs of unusual aridity in the salt and gypsum deposits of Silurian and other early times; there had been red beds in the Devonian period, and in the Keweenawan; there had been marked restrictions of life, as at the close of the Ordovician; there had been extensive geographic changes in earlier Paleozoic periods; and there had been foldings of surpassing intensity in Archean and Proterozoic times. The peculiarity of the Permian was the complexity of the combination, and the extent of the glaciation and aridity.

The chronological setting of the combination lends some advantages to its study. It lies in the midst of geologic history, with periods of climatic uniformity and polar geniality both before and after it. No appeal can be taken to a supposed final cooling of the earth, or to any senile condition. It was an episode in the midst of a long history, and its problems must be faced with this setting in mind.¹

¹ It is impracticable to discuss these problems here, but they are considered in the authors' larger work, Vol. II, pp. 655-677.

THE MESOZOIC ERA

CHAPTER XXIII

THE TRIASSIC PERIOD

FORMATIONS AND PHYSICAL HISTORY

During the closing stages of the Paleozoic, when the sea was excluded from the area between the growing Appalachians and the Great Plains, Appalachia appears to have suffered deformation. One result of this deformation was the development of elongate troughs upon its surface, roughly parallel to the present coast. These troughs became the sites of deposition, and the sediments laid down in them constitute the only representative of the Triassic system in the eastern part of the continent. The open sea seems to have been completely excluded from the western interior by the beginning of the Triassic period, though sedimentation was in progress over considerable areas between the meridians of 100° and 113°. Some of these areas appear to have been the sites of salt seas and some of fresh lakes, while still others were probably without standing water. Between the meridians named, many areas of relatively high land probably interrupted the continuity of sedimentation. On the western coast, the ocean began to gain on the continent about the close of the Paleozoic, and the shore of the Pacific was presently shifted eastward to the vicinity of the 117th meridian in the latitude of Nevada.

In keeping with these changes in geography, Triassic strata are known in three regions: (1) The Atlantic slope east of the Appalachians; (2) the western interior; and (3) the Pacific coast. The strata in these three regions are in many ways unlike.

The Eastern Triassic — The Newark Series

Distribution. The Triassic system of the east occurs in spots from Nova Scotia to South Carolina, as shown in Fig. 464. Its



Fig. 464.— Map showing the known distribution of the Triassic system in North America (black areas), with conjectures as to its presence where buried (lined areas), and its absence where it was once present (dotted areas).

several areas are mostly elongate in a northeast-southwest direction. The principal areas are: (1) About the Bay of Fundy; (2) in the Connecticut River valley; (3) from the Hudson River to Virginia; and (4) disconnected areas in Virginia and North Carolina. The beds of these several areas have been grouped under the name *Newark*¹ (Newark, N. J.).

The rocks of the Newark series² include all the common varieties of fragmental rocks, some of which are developed in unusual phases. Sandstones and shales predominate, but there are abundant conglomerates, some breccias, and, locally, limestone and coal.

The conglomerates. Conglomerate lies at the base of the system in many places, and is made up chiefly of material from the underlying crystalline schist. But the conglomerates are not simply basal. Some of them represent the border phase of beds which grade laterally into sandstone, and even into shale. The chief constituent of the conglomerate is quartz, the most resistant part of the underlying terranes; but quartzite and crystalline schist appear in the conglomerate, and locally limestone is its principal constituent.

The exceptional coarseness of the conglomerate in some places has been thought to call for unusual conditions of origin. It has been conjectured that it was formed at a time when glaciers existed in the region. It should be noted, however, that this suggestion was based on the supposed demand for some exceptional agent of transportation, rather than on any direct evidence of glaciation. In general, the materials of the conglomerate are too well assorted to be the immediate product of glaciation, and the stones and boulders do not bear the marks of ice. These points would lose much of their force if the conglomerate were deposited by glacial drainage; but in the absence of all certain evidence of glacial or glacio-fluvial origin, it seems more prudent to regard the conglomerate as a formation of terrestrial or shallow-water origin.

The sandstone and shale. Sandstone and shale make up the

¹ For an account of the Newark series see Russell, Bull. 85, U. S. Geol. Surv., 1892. Full bibliography to date of publication.

² The Connecticut valley and New York-Virginia areas are best known, and the descriptions of the formations here given apply especially to them.

great body of the Newark series, and both possess distinctive characteristics. Their prevalent color is red, though there are shales which are black, and sandstones which are gray. Except locally, the series is poor in fossils. Some of the sandstone is arkose, that is, contains a considerable amount of feldspar, and both sandstone and shale contain much mica. Both these constituents abound in the metamorphic rocks from which the Newark sediments were chiefly derived.

Conditions of origin. The character of the Newark formations and their fossils, mainly land plants, footprints of reptiles, and fresh- or brackish-water fishes, indicate that they are of continental rather than marine origin, though the precise manner in which they were laid down is not known. That deformation of the surface of Appalachia, which had been reduced nearly to planeness by erosion, gave rise to elongated depressions in which the Triassic sediments were deposited, seems certain. The depressions may have been due to warping or to faulting, or partly to the one and partly to the other (Figs. 465 and 466), and their development may have progressed as deposition went on. Some of them may have been broad river valleys, which, in the general uneasiness which marked the close of the Paleozoic era, became sites of deposition. However formed, these depressions in the surface of the present Piedmont region became the sites of lakes, bays, estuaries, dry basins, or aggrading rivers. Lacustrine, estuarine, and fluvial conditions may have alternated from time to time in the various places where sedimentation was in progress, and perhaps the sea gained access to some of them from time to time.

The considerable thickness of the sediments, taken in connection with their decisive evidences of shallow-water or subaërial origin, such as ripple-marks, sun-cracks, tracks of land animals, etc., indicate either that inclined deposition prevailed, or that subsidence of the areas of sedimentation accompanied the deposition. For the adequate supply of the detrital material, it would seem that the lands bordering the areas of deposition were raised, relatively, as the troughs were filled. The general conditions of accumulation may have been similar to those under which the Catskill formation was deposited at an earlier time.

Former extent. It is possible, and perhaps probable, that the areas of the Newark series from Virginia to South Carolina were once connected with one another, and with the Virginia-New York area, though such connection has not been demonstrated. It has even been suggested that the Newark of the New York-Virginia area was once connected with that of the Connecticut valley, and this with that of Acadia, and that the separation was effected by erosion; but this suggestion does not seem well founded.¹

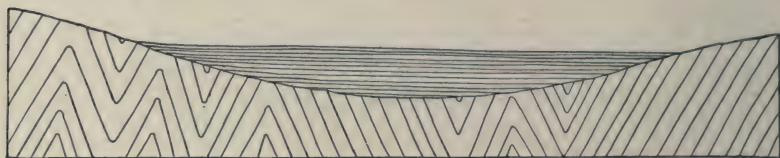


Fig. 465.—Diagram showing the development of a trough, now partly filled by sediment, by warping.

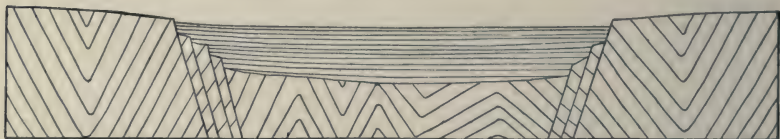


Fig. 466.—Diagram showing the development of a trough by faulting.

Igneous rocks. Igneous rocks are associated with the sedimentary beds in dikes and in sheets interbedded with the shales and sandstones. Some of the sheets are extrusive, having been poured out on the surface of the inferior beds and subsequently covered by sediment; others are intrusive (*sills*), having been forced in between the layers of sedimentary rocks after the latter were deposited. Certain isolated bodies of igneous rock may represent volcanic plugs. The sheets of igneous rock (usually called trap, though largely basalt) vary in thickness from a few feet to several hundred.

¹ For summary of the Trias of Connecticut, see Davis, 7th Ann. Rept., U. S. Geol. Surv., or a fuller and later account in the 18th Ann. Rept., Pt. II. See also the Holyoke folio, U. S. Geol. Surv., and for the Pomperaug area, Hobbs, 21st Ann. Rept., U. S. Geol. Surv., Pt. III.

Structure. The structure of the Newark series is generally monoclinical. In the Connecticut River valley the dip is about 20° (10° to 25°) to the eastward. In the New York-Virginia area¹ also the structure is monoclinical, the dip being to the northwest (10° - 15°). This contrast of dips between the New England and New Jersey areas has been thought to support the suggestion that the strata of the two areas are parts of one huge anticline, from the broad crest of which the beds have been removed. The strata are otherwise somewhat deformed, though never closely folded. The series is faulted extensively, and in a somewhat complicated manner.

Thickness. On account of the faulting, the thickness of the Newark series is difficult of determination. In the Richmond area



Fig. 467.—Structure of the Newark series on the James River, Richmond area, Va. AA, minor flexures; ff, faults. Structure of the deeper parts hypothetical. The heavy black band represents coal. (Shaler and Woodworth, U. S. Geol. Surv.)

of Virginia, it is estimated at something more than 3,000 feet; in New England, at 7,000 to 10,000 feet; and in New Jersey even more.

Correlation. The stratigraphic relations of the Newark series in the United States would not determine its age. It lies unconformably on rock which is mainly pre-Cambrian, and is overlain unconformably by Comanchean (Lower Cretaceous) beds. About the Bay of Fundy, however, the rocks lie unconformably on the early Permian. The physical relations of the Newark series therefore show that it is post-early-Permian, and pre-Comanchean. Between the Permian and the Comanchean there are two periods, the Triassic and the Jurassic. In referring the series to the former, the chief reliance is on the fossils, and on the same basis it is believed to represent only the later part of the period.²

¹ For summary of the Newark of New York and New Jersey, see Kümmel, Rept. of the State Geologist of New Jersey, 1896, and Jour. Geol., Vol. VII.

² Rice and Gregory would make the Newark the approximate equivalent of the Keuper of Europe. Bull. 6, State Geol. and Nat. Hist. Surv. of Conn.

In the West

The deposits of the western interior.¹ The interior area of sedimentation, chiefly between the 100th and 113th meridians, had its southern limit, so far as now known, near the southern boundary of the United States, while at the north it extended into Canada. This area is believed to have been cut off from the Gulf by land in eastern Texas, or if it had connection with the sea, it was probably slight. Into this interior area of sedimentation, detritus was borne from the surrounding lands. Some of the deposits were probably laid down by streams, some in fresh lakes, and some in bodies of salt water, as in the Permian period. Fresh-water fossils (unios) are found locally, as in New Mexico. The structure of some of the sandstone is such as to suggest an eolian origin.

The deposits of the period are in large measure concealed by later beds, but they are exposed at various points where the strata have been warped, and the overlying beds removed by erosion. The most easterly outcrops are in Texas, Oklahoma, and South Dakota. The system may underlie later formations between these localities and the Rocky Mountains. Red beds which are thought to be Triassic outcrop interruptedly along the eastern base of the Rocky Mountains from British America to New Mexico. These beds are thin, and contain more or less gypsum and sometimes salt. Occasionally they contain fossil leaves.

Farther west, Red beds have representation among the surface rocks. Some of these beds are perhaps Triassic; but in much of the western interior, the undifferentiated Triassic and Permian rest conformably on the Carboniferous (Pennsylvanian), though occasionally they overlap it and rest upon pre-Cambrian formations. In southwestern Colorado and eastern Utah, the Trias rests unconformably on older, deformed, unfossiliferous red beds (presumably Permian) and on strata of Pennsylvanian age.²

Thickness. In the eastern part of this western area, the Triassic system is thin, sometimes no more than 100 feet. To the west it

¹ There is some doubt about the age of most of the beds formerly referred to this system. The tendency of later study has been to refer more and more of them to the Permian. See references under Permian, and Hill, *Physical Geography of the Texas Region*, folio U. S. Geol. Surv.

² Cross; See footnote p. 662.

thickens, reaching to 2,000 to 2,500 feet in the Uinta Mountains, beyond which it again becomes thinner.

On the Pacific Slope¹

The Triassic system has its greatest development in America along the Pacific coast. In the latitude of Nevada, the Pacific seems to have extended eastward over the site of the Sierras to



Fig. 468.—Chugwater (Triassic) Red Beds near Shell, Wyo. (U. S. Geol Surv.)

longitude 117° (approximately). The shore line of the Pacific farther north has not been definitely located. It was probably irregular, and, in general, several degrees farther east than now, well up into British Columbia. Between the latitudes of 55° and 60° , the sea is believed to have crossed the present Cordilleran² belt, though this northern bay east of the Rockies was probably not connected freely with the areas of sedimentation in the western interior. Marine beds of the Lower Trias are found as far east as

¹ King, Geol. Surv. of the 40th Parallel, Vol. I, gives an account of the Triassic as far west as the Sierras in this latitude. See also many of the California folios of the U. S. Geol. Surv., and the Roseburg, Ore., folio.

² Dawson, *Science*, March 15, 1901.

eastern Idaho, and the sea probably reached this region by way of Utah, Nevada, and Southern California. Later formations of the system are not found east of western Nevada and eastern Oregon.¹ The Triassic system is found as far north as Alaska.

The published measurements assign the system the great thickness of 17,000 feet (maximum) in the West Humboldt range of Nevada, where it rests on pre-Cambrian terranes. To have supplied such a volume of sediment, the land to the east must have been high, or repeatedly renewed, to counterbalance the waste, unless the great thickness is due to oblique deposition.

The succession of faunas in the Trias of the Pacific coast indicates that considerable changes in the physical geography of the northern Pacific were in progress during the period. These will be referred to in connection with the faunas of the system.

Climatic Conditions

The wide distribution of gypsum and salt in the Triassic system, not only of America but of Europe, is good evidence of wide-spread aridity. The prevalent redness of the system, in other continents as well as our own, is also commonly regarded as an indication of aridity. Some of the peculiarities of the Newark conglomerate also might find their explanation in aridity. In an arid climate, expansion and contraction due to changes of temperature are so great as to be effective in disrupting rock if it is not covered by soil. Under such circumstances, much coarse debris originates, largely of rock which is undecomposed. Violent storms (cloud-bursts), which often characterize arid climates, might account for the transportation of debris from the place of its origin to the place of its deposition. For the formation of abundant debris in this way, steep slopes are needful, for gentle slopes and flats soon get a covering of mantle rock which prevents the disruption of the rock beneath. If this was the origin of the coarse materials of the conglomerate, their rounding and wear would have to be attributed to the waves of the body of water in which deposition took place.

¹ Stanton, Jour. Geol., Vol. XVII.

Close of the Trias

Considerable geographic changes marked the close of the Triassic period in eastern North America, bringing the areas which had been the sites of deposition to higher levels, faulting the rocks, and affecting them by igneous intrusions. These changes were comparable in extent and importance to the changes which separate the various systems of the Paleozoic, but they were not of continental extent.

In the western part of the United States, the separation of the Triassic period from the Jurassic was not pronounced, and the sedimentary history of much of the western half of the continent seems to have run an uninterrupted course from the beginning of the Permian to the later part of the Jurassic. The case may have been somewhat different north of the United States, for in British Columbia and in the adjacent islands, Triassic and older formations were upturned, deeply eroded, and again submerged before the beginning of the Cretaceous. The great igneous formations associated with the Trias of the northwest appear to have been made during the Triassic period, rather than at its close.

FOREIGN TRIASSIC

Europe

In Europe, the Trias is exposed in many widely separated places, the largest being in northwestern Russia; but the system is better known in the western part of the continent. In England, it is unconformable on the Permian, but on the continent, generally conformable.

The system has a marine and a non-marine phase. The non-marine (or *Triassic*) phase prevails throughout the northern part of the continent, while the marine (or *Alpine*) phase is found farther south. The former resembles the Permian of Europe, and the Permian and Triassic of the United States.

In general, the Upper Trias is more wide-spread than the Lower, especially in the southern part of the continent, and is marine over

a wider area. The principal subdivisions recognized in Britain and Germany are the following:

<i>Britain</i>	<i>Germany</i>
Rhaetic	Keuper
Upper Trias	Muschelkalk
Lower Trias	Bunter

Northern Europe. The Bunter formation of *Germany* was deposited chiefly in lakes, inland seas, and on land, as shown by the fossils, the beds of salt and gypsum, and the dune structure of some of the sandstone. The name has reference to the high colors of the formation, red predominating. Toward the top of the formation, thin beds of marine origin are intercalated locally with the



Fig. 469.—Sketch-map of Europe showing areas of sedimentation in the early part of the Triassic period. The broken lines represent areas of non-marine deposits; the full lines, areas of marine deposits. (After De Lapparent.)

others, showing that changes in the relation of land and water were in progress, and that the sea gained on the land toward the close of the epoch.

The *Muschelkalk* is a limestone formation and records the further encroachment of the sea. Its fauna has been thought to indicate that the water in which it lived was not the open ocean, but a body of water comparable to the Black sea or the Baltic¹.

The *Keuper* formation resembles the Bunter, and, like it, is marine in its upper portion, and is followed by the marine beds of the Jurassic period. The Keuper contains a little coal (not workable), a common accompaniment of shallow-water and marsh formations.

In *England* the system is often known as the New Red Sandstone, though formerly the Permian was also included under this term. It differs from the Trias of Germany chiefly in that the marine member of the German system is absent in England. Both salt and gypsum occur in workable quantities in some parts of England.

In *southern Sweden*, the Trias contains coal. The system here was probably once continuous with that of Germany, and may still be, for borings show that it underlies parts of the North German lowland. The Triassic beds of most of *Russia* are similar to those of western Europe.

The non-marine formations of red color so characteristic of the Triassic system both in North America and Europe afford another striking inter-continental analogy, and doubtless point to a common cause, or to similar wide-spread conditions.

Southern Europe. The Alpine or marine phase of the Triassic has its best development in the eastern and southern Alps, and is made up of thick beds of limestone, often dolomitic, alternating with thinner beds of clastic rock. The limestone and dolomite are much more resistant than the associated shales, and as a result, erosion has developed a distinctive topography (*Karst* topography) at several points in the southern Alps — a topography so striking that the localities where it is seen have become the objective point of travel, both for geologists, and for lovers of wild and picturesque

¹ Kayser, op. cit., p. 286.

scenery. In these regions the dolomite (limestone) stands up in bare, bold-faced walls, peaks, and towers, surrounded and separated by valleys and passes clothed with abundant vegetation. The decay of the projecting limestone leaves little soil behind, and the little which is formed is promptly carried away by wind and rain.

The Trias of the Italian Alps is the source of the Carrara marble. The Trias of the western Alps is largely non-marine, and in some parts of Switzerland the Upper Trias contains coal and igneous rocks.

Other Continents

Asia. The marine phase of the system, similar to that of southern Europe, is continued eastward to southern Asia. It is also found in the high latitudes of Asia, including numerous islands north of the mainland. The Trias is generally conformable on the Permian and beneath the Jurassic.

South America. No marine deposits of Triassic age are known east of the Andes, but coal-bearing Trias occurs in Argentina and Chile, and marine beds at various points in the Andes. Thus it is clear that the site of parts of this great system of mountains was beneath the sea in the Triassic period.

The Triassic system is represented also in South Africa, Australia, New Zealand, and New Caledonia.

THE LIFE OF THE TRIASSIC PERIOD

The remarkable physical conditions that dominated the land and impoverished its life in the Permian period still held sway during the earlier part of the Triassic. In their general biological aspects, as in their physical conditions, the two periods were much alike. Toward the close of the Triassic there was a pronounced change. The land became lower and the sea encroached upon it, bringing about appropriate changes in life. Nearly all that is known of North American Triassic life belongs to the later portion of the period.

The Plant Life

The record of the vegetation is very imperfect, and it was probably scant in reality, for broad saline basins and arid tracts are inhospitable to plants. The Triassic was distinctly an age of gymnosperms. Ferns and fern-like plants still held an important place, and the *Equisetales* were more important than now; but the dominance of these types was past. The great lycopods, too, were almost gone, though sigillaries were among their lingering representatives. Among gymnosperms, the cordaites had declined, but conifers of the types that came in during the Permian, and kindred new ones, were prominent. The cycadean group occupied the place of central interest. The *Bennettitales*, formerly called cycads, abounded, and from them the true cycads sprang later. The ginkgos (*Ginkgoales*) diverged from the ancestral cordaites at about this time.

The calamites had given place to true equiseta, which were represented by forms that were gigantic in comparison with modern types. In the far east and in the southern hemisphere, the *Glossopteris* and its allies constituted a marked feature of a flora whose general aspect was much like that of the preceding Permian in the same regions.

The Triassic floras of Europe and America, so far as known, were much alike, and both bore a scrawny pauperitic aspect that reflected the hostile conditions against which they struggled, conditions for which the stunted conifers of to-day stand as representatives.

In the closing stages of the period, a much ampler flora seems to record some amelioration of the inhospitable conditions. The larger part of the known American fossils belong to this stage. The Richmond coal-beds of the Newark series, probably the product of marsh vegetation, contain great numbers of equiseta and ferns, but almost no conifers and few cycadeans. A few plant fossils have been found in Mexico, Arizona, and California.

The Land Animals

The physical conditions of the Permian and Triassic periods were so similar that adaptation to the conditions of the first would

seem to have been a fitting preparation for life in the second. Yet, in spite of this fact, there was a great break in the succession of land life, so far as the known record shows. What became of the Permian vertebrate faunas of North America is unknown, for between the horizons yielding Permian fossils of land animals, and those yielding corresponding Upper Triassic fossils, there are great thicknesses of red sandstone barren of fossils of all sorts, so far as now known, and the Upper Triassic (Keuper) fauna does not appear to have descended from the Permian. In Africa there appears to have been a much less serious break between the land life of the Permian and that of the Trias. In other continents few fossils of land life of the early types have been found, and the record of the Middle Trias is but little less meager. Of the life of the Upper Trias the record is much fuller. The period was one of great transitions, in which many types were initiated, while only a few were carried to their maximum development.

There is abundant proof of the intermingling of European and American land faunas late in the Triassic period, for at this time there were, in North America, representatives of groups that had lived in Europe since the early Permian, but which had never before appeared in our continent, so far as now known.

The *amphibians* had lost the foremost place they held in the Permian, though still numerous (but not in North America in the early part of the period). Before its close, however, they entered upon a rapid decline, from which they never recovered. Ancestors of the whole tribe of terrestrial vertebrates, they soon became its most insignificant representatives.

The strange ancestral *reptiles* evolved rapidly. The branch with the mammalian strain (p. 672, Fig. 470) seems to have been left far behind by the more distinctively reptilian branch, which developed greatly in the closing stages of the period when the dryness was ameliorated and vegetation began again to flourish. Before the close of the period, every important group of the class had its representatives. The crocodilians, the flying saurians, and the scaled reptiles (lizards, snakes, etc.) came in near the close of the period, as some of the older types were disappearing.

A foremost feature of the life was the advent and rapid evolu-

tion of the dinosaurs (terrible saurians), the reigning reptilian dynasty of the era. They were at first of generalized types, but

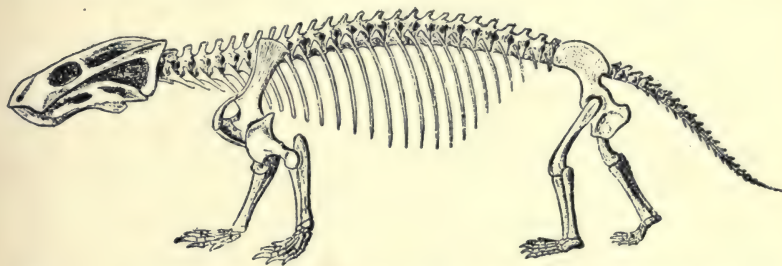


Fig. 470.— *Oudenodon trigoniceps*; an anamodont (or dicynodont) from the Karoo formation of South Africa, so similar to forms of the Trias in Wyoming as to be distinguished from them with difficulty. (After Broom.)



Fig. 471.— A Triassic dinosaur of the Connecticut Valley, *Anchisaurus colurus*, restored by Marsh, 1-30 natural size.

later became more specialized, and diverged widely. While some were small and delicate in structure, others were gigantic and ungainly. Carnivorous forms only (*Theropoda*) are known in the

Trias, and most of them were not especially large. Their general form is indicated by the partially restored skeleton shown in Fig. 471. The strong development of the hinder parts, the relative weakness of the fore limbs, and the kangaroo-like attitude, are the most obvious features. The bones of these upright-walking forms were hollow, and certain other structural features resemble those of birds. The reduction of the functional toes of the hind feet to four, with one of them much shorter than the others, caused their three-toed tracks to be mistaken for those of birds, until recently. Even in the Triassic period, the dinosaurs ranged widely, living in the Rocky Mountains, along the Atlantic coast from Carolina to Prince Edward Island, in western Europe, India, and South Africa.

Before the close of the period both branches of the reptilian tribe sent delegations to sea, the one represented by the *ichthyosaurs* (Fig. 489) and the other by the *plesiosaurs*. It is not difficult to find good reasons for this sea-ward movement. Besides the tendency of every masterful race to invade all accessible realms, the notable extension of the sea before the close of the period invited the adaptation of land animals to an aqueous habitat, for the shallow waters with their prolific life, creeping in upon the land, set tempting morsels before the voracious reptiles, while the reduction of the land areas and their terrestrial feeding-grounds, intensified by their own multiplication, encouraged a movement to the sea.

The advent of mammals. Of peculiar interest is the appearance of early forms of non-placental mammals. They were small, and so primitive in type that it is not altogether certain that they were mammals; but they are commonly regarded as such, with kinship to the marsupials. Their appearance while reptiles were yet dominant suggests that mammals diverged from the primitive stock much earlier. In view of the mammalian dominance of later times, it is note-worthy that the non-placentals developed but slowly and feebly during the Mesozoic era. It is an open question whether placental mammals are the descendants of the Mesozoic non-placentals, or whether they had an independent origin.

The Marine Life

The reduction of marine life of the shallow-water type during the Permian (p. 673) was continued into the Triassic period, and since its remains are in sediments now buried, such record as it made is mainly concealed. This was especially true of North America. To trace the shallow-water marine life of the Permian into that of the next period, it is necessary to bring together evidence from different continents. The question of supreme interest is the way in which the epicontinental sea life, crowded to a minimum

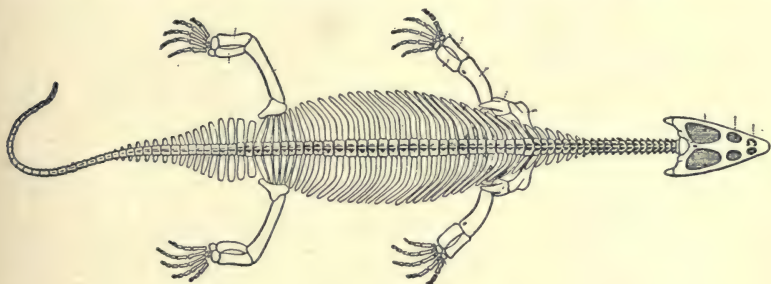


Fig. 472.— A Triassic sauropterygian, *Lariosaurus balsami*, restored; about $\frac{1}{11}$ natural size; from the Muschelkalk, Lombardy, Italy. (After Woodward.)

habitat between the land and the deep sea, maintained its continuity, transformed its species, and later re-peopled the shallow waters when they again became more extensive in the closing stages of the Trias and later.

When the sea readvanced on the North American continent, it was chiefly from the Pacific, but there were also incursions up the MacKenzie Valley and from the Gulf of Mexico. It is not clear that the sea completely withdrew from the present land area on the Pacific coast after the Permian; but the fossils so far recovered from the Trias of this region do not give clear evidence of continuous submergence of an area such as to allow the development of a definite provincial fauna.

The transition tracts. It was otherwise on the Eurasian continent. While the sea withdrew from the northwestern part of

Europe during the Permian period, it lingered about the Mediterranean, in Russia, Turkestan, and northwestern India, and probably on the continental platform in or near Siberia. The Mediterranean, the Himalayan, and the Siberian regions are the best known tracts into which the shallow-water marine life of the late Paleozoic retreated and underwent transformation into the early provincial faunas of the Mesozoic. It is quite certain that there was at least one other area where important faunal reorganization took place at about this time, for a notable fauna suddenly appeared in the Middle Triassic, which does not seem to have originated in any of these three districts.

In each of these three areas an important remnant of Paleozoic sea life seems to have undergone a radical and perhaps rather rapid evolution, such as might be anticipated from the crowding of the great faunas of earlier times into such limited areas. From these areas the new faunas spread when the sea again extended itself upon the land.

The transition faunas. The most complete record of the transition from Paleozoic to Mesozoic marine life is found in India. Beds containing fossils characteristic of the Permian are overlain conformably by beds containing forms characteristic of the Mesozoic. In the Permian beds there are forms foreshadowing the Mesozoic types, and in the beds above there are Permian types that lived on and mingled with Mesozoic forms. The transition fauna of the Mediterranean region appears to have been less rich than that of India. Concerning the early stages of the Siberian fauna, little is known; but its peculiarities, as revealed in a later stage of the early Trias, leave little doubt of its independence of origin.

General nature of the faunal changes. In nearly all Paleozoic faunas, brachiopods were a leading element of the marine faunas, while trilobites, crinoids, and corals, each in turn, gave distinctive character to the successive faunas. In the Mesozoic era, the ammonites took the first place, followed by the pelecypods and the gastropods. The ammonites (Fig. 473) are peculiarly fitted for distinguishing successive horizons, not only because they were free forms, measurably independent of bottom conditions, but because they were steadily and rapidly advancing in organ-

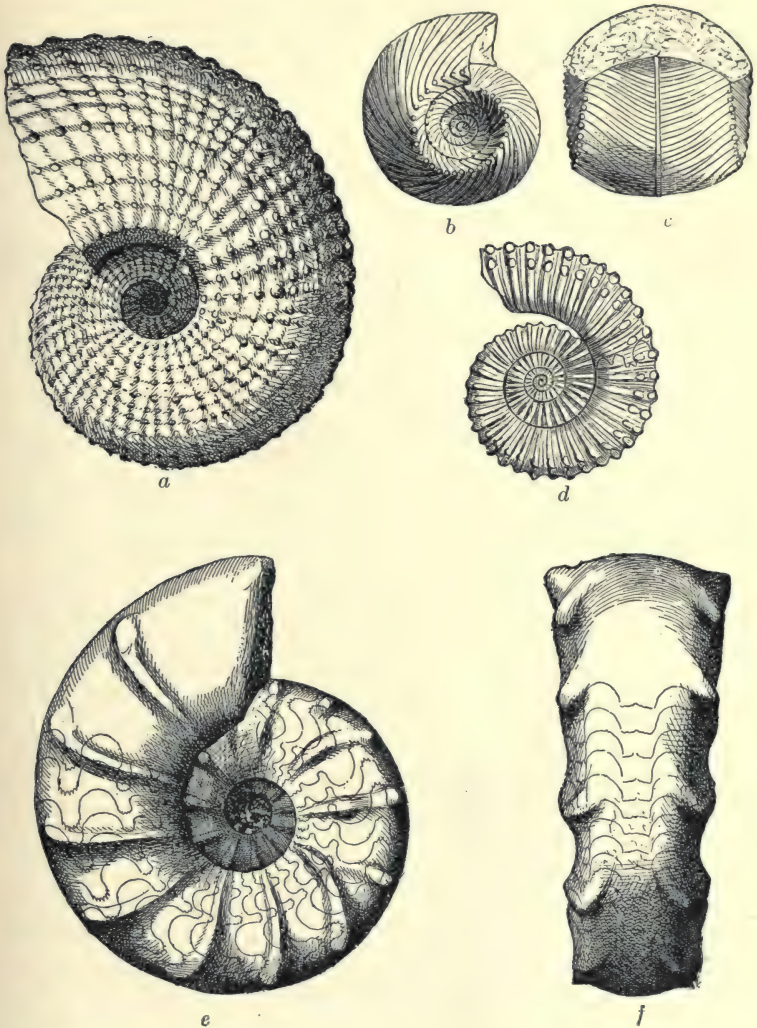


Fig. 473.—A Group of Triassic Cephalopods. *a*, *Trachyceras austriacum* Mojs.; *b-c*, *Tropites subbullatus* Hauer; *d*, *Choristoceras marshi* Hauer; *e-f*, *Ceratites nodosus* de Haan, lateral and ventral views of the shell.

ization, and because their shells were so constituted as to record their progress.

The earliest fauna was markedly restricted. This may be more apparent than real on account of the imperfection of the accessible record; but it was doubtless real in some measure, and due to the physical limitations already sketched. At the same time, there was an increase in differentiation. The conditions which repressed the life, reducing the number of individuals, species, and genera, forced them to diverge more and more, in order to accommodate themselves to the conditions inhospitable to life. This is shown best in the development of the land and fresh-water life, but to some extent also in the marine life.

The geographic suggestions of the faunas. A great group of ammonites, embracing more than 200 species, formed the leading features of the early Indian fauna. The alliance of the Indian forms with those of North America is so close as to indicate that before the close of the early Trias, migratory connections had been established between India and western America.

Somewhat later in the early Trias there appeared in the Siberian region (Olenek River) a fauna having some of the same genera as the Indian. Closely related species are found in Idaho. If there was connection between the Indian and Siberian regions, it would be possible for Indian species to reach America either by way of Siberia and the Arctic coast, or by the Pacific sea-shelf, and slight changes, involving submergence or emergence in the region of Bering Strait might change the combination of the faunas.

The Indian and Siberian provinces seem to have been distinct from the Mediterranean province throughout the earlier Triassic; but in California a few fossils have been found which are characteristic of the earlier Triassic of southern Europe.

The early Triassic faunas of central Europe were very variable, a part being developed apparently in fresh water, a part in isolated seas, and a part perhaps in dependencies of the ocean. The marine life was scanty, and its origin and relations uncertain; but it seems to have been largely independent of the Mediterranean basin.

By the middle of the Triassic period the faunas had begun to intermingle, and to lose their provincial characteristics. The Med-

iterranean fauna gained access to the Indian basin and to our western coast, and counter-migrations were of course made possible. At about the same time, the Siberian fauna had access to western United States.

During the later stages of the period, a rich marine fauna flourished in California. Many of its species were identical with those of the Mediterranean and Himalayan regions, or closely allied to them. It is therefore inferred that these provinces were in free communication, so far as marine life was concerned, with the west American coast. The Upper Trias of British Columbia, on the other hand, contains a different fauna, including a type that belongs to the Siberian group. The British Columbian fauna is perhaps to be regarded as the descendant of the Idaho fauna of the early Trias, with additions from Siberian sources, while the California fauna is perhaps a derivative from the Mediterranean and Himalayan provinces by some different route. Present knowledge, however, is not sufficient to show the precise nature of the migrations between Europe, Asia, and America during Triassic times.

The most conspicuous feature of the Triassic faunas was the reascendancy of the *cephalopods* in the form of the *ammonites*, which had a marvellous development during the period, reaching a thousand species. Their evolution was the more notable because the structural changes were conspicuous, and showed plainly the advance of each stage over the preceding. While early types still persisted, the closely coiled, intricately-sutured forms predominated. The first known cephalopods of the cuttlefish type appeared at this time. The deployment of the cephalopods was therefore more varied and comprehensive than ever before, though they did not reach their culmination till the next period. Old forms, orthoceratites and goniatites, made their last appearance in this period. The remarkable commingling of old and new types makes this one of the most instructive assemblages in the history of the cephalopods.

A similar commingling of transitional forms was presented by the *gastropods*. The progress of the bivalves was scarcely less real, though they do not show the transition from ancient to modern so conspicuously. Their numbers were large, and most of their genera

modern, some being identical with those now living. With the modern types there were about half as many that still bore a Paleozoic aspect.

The dominant *brachiopod* types of the late Paleozoic were distinguished by extended hinge lines (spirifers, orthids, etc.), while the narrower beaked or rostrate forms were in a respectable minority. In the Triassic period, the rostrate forms (*Rhynchonella*,

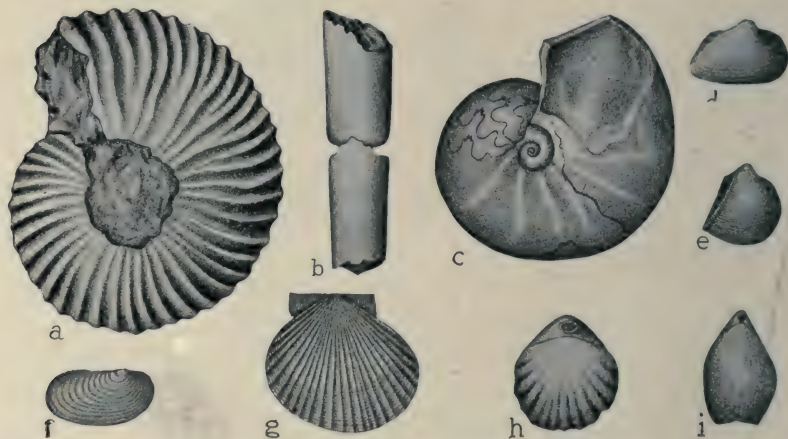


Fig. 474.—A Group of Marine Triassic Fossils. *a*, *b*, and *c*, cephalopods: *a*, *Ceratites whitneyi* Gabb; *b*, *Orthoceras blakei* Gabb; *c*, *Meekoceras*. *d*-*g*, pelecypods: *d*, *Corbula blakei* Gabb; *e*, *Myophoria alta* Gabb; *f*, *Myacites humboldtensis* Gabb; *g*, *Pecten deformis* Gabb; *h* and *i*, brachiopods: *h*, *Rhynchonella æquiplicata* Gabb; *i*, *Terebratula humboldtensis* Gabb.

Terebratula, and allied genera) became predominant, and have remained so ever since. (Compare Figs. 474 and 419.)

Although *echinoderms* are not abundant in the Triassic fauna, the period marks the transfer of leadership from the crinoids to the sea-urchins, and a structural change in the latter. Beginning with the Triassic, the echinoids had twenty rows of plates in belts of two rows each, whereas the Paleozoic forms had more. At first they retained the previous pentamerous symmetry, but later this gave place to a bilateral symmetry. Starfishes and brittle-stars were present, but not abundant.

While *corals* were rare in most places, they were rather abundant in favored localities. Some of them resembled the Paleozoic forms in being simple and cup-shaped, but the compound species took on the modern (*hexacoralla*) form, and the compound Paleozoic (*tetracoralla*) type disappeared. These later compound corals do not seem to have descended from the compound Paleozoic forms, but from some simple type.

While the general aspect of the Triassic marine faunas was revolutionary, it is important to note, in view of beliefs once current, that it was transitional, and not an abrupt substitution of a new fauna for an old one. Paleozoic types lived side by side with later forms, though usually represented by new genera. This overlapping and commingling of old and new clearly indicates the gradation of the earlier into the later. The transition was extraordinary in the apparent rapidity of its progress, and in the extent to which it affected all classes. The fact that most of the new types were already present in the earliest Triassic, indicates that the transition was chiefly in the Permian. The fundamental cause was, with little doubt, the readjustment of the earth's surface to internal stresses, and the physiographic and climatic changes consequent upon this readjustment.

Marine reptiles seem to have thriven in the western part of our country, especially in the middle and later Trias. The numerous ichthyosaurs found in the later Triassic beds, and their peculiarities, suggest that this may have been a center of dispersion of these reptiles. With the ichthyosaurs were other reptiles (*thalattosaurs*) unknown elsewhere.¹

¹ Merriam, *The Thalattosauria*, Cal. Acad. of Sci.; *Triassic Ichthyosauria*: Memoirs of the Univ. of Cal., 1908.

CHAPTER XXIV

THE JURASSIC PERIOD

FORMATIONS AND PHYSICAL HISTORY

The eastern part of the continent. Jurassic formations have not been identified certainly in the eastern half of the continent, but there are beds outcropping along the western margin of the Coastal Plain in Maryland that may belong to this system. In constitution, structure, and all physical relations their alliance is with the Comanchean (Lower Cretaceous) of the same region, and since their fossils are indecisive, this seems, at present, their best correlation.

Erosion seems to have been the leading geologic process in the eastern part of the continent during the period. Its effectiveness may be judged by the fact that both the uplifted and deformed Triassic system and the Appalachian mountain region farther west were essentially base-leveled before the Comanchean period was far advanced. The sediments worn away from these areas were deposited somewhere, presumably east of the present coast. Erosion seems to have been in progress also in the eastern interior over most or all the area which emerged during the closing stages of the Paleozoic.

The western interior. In contrast with the eastern half of the continent, deposition was in progress, probably, in some parts of the western interior, though the possible early Jurassic beds of this region have not been clearly differentiated from the Trias. There is perhaps room for doubt whether the early and middle parts of the system have much representation in this region.

Late in the period, an arm of the sea extended itself over a large tract in the western interior (Fig. 475), covering much of Wyoming,¹

¹ Logan, Jour. Geol., Vol. VIII, p. 241; Knight, Bull. 45, Wyo. Exp. Station, and Bull. Geol. Soc. of Am., Vol. XI, pp. 377-388, and the Wyoming folios of the U. S. Geol. Surv.



Fig. 475.— Map showing the areas where the Jurassic system appears at the surface in North America. The conventions are the same as in preceding maps.

Montana,¹ Utah, and Colorado, and parts of several other states² (Fig. 476). This is shown by the presence in these states of sedimentary beds containing marine fossils of early Upper Jurassic age. The beds are chiefly exposed in the mountains (Wasatch, Uinta,

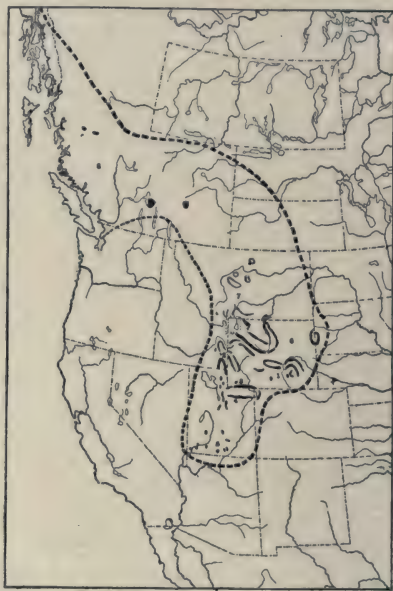


Fig. 476.-- Map showing the general relations of land and water in the western part of North America during the later part of the Jurassic period. The black areas represent known areas of Upper Jurassic. The dotted line is the conjectured outline of the bay. (After W. N. Logan.)

Black Hills, etc.) where the erosion which followed the uplift and deformation of the strata has discovered their edges.³

The avenue through which the sea reached the western interior has not been determined, but the fossils of the interior are so unlike those of the Californian coast as to lead to the inference that the waters of the interior did not come in from the west. The identity

¹ See the Montana folios, U. S. Geol. Surv.

² For South Dakota, see Darton, 21st Ann. Rept., U. S. Geol. Surv., Pt. IV. and the folios, U. S. Geol. Surv.

³ In addition to the above folios, U. S. Geol. Surv., see those of Colorado.

of many species from the Upper Jurassic beds of the Queen Charlotte Islands and British Columbia with those of the western interior, imply shallow-water connection of these areas. Whether this connection was through British Columbia direct, or by way of Alaska and down the east side of the Rocky Mountains, is not known. The presence of fresh-water beds (the Morrison [or Como] beds of Colorado, Montana, and Wyoming), sometimes regarded as of late Jurassic age in some parts of the western interior, would, were



Fig. 477.—Lower part of the LaPlata (Jurassic) sandstone, southwest of La Sal Mountains, Utah. (Cross, U. S. Geol. Surv.)

their age established, show that the sea-water withdrew before the end of the period.

Marine Jurassic limestone has been reported recently from western Texas,¹ and though the exposures are limited, their connections are probably southward with the Jurassic of Mexico, where the system is somewhat wide-spread.

The Pacific coast. Marine deposition was in progress on the Pacific coast² (California and Oregon), though much of the system

¹ Cragin, Jour. Geol., Vol. V; and Hill, Am. Jour. Sci., Vol. II, 1897, p. 449, and Physical Geography of Texas, Topographic Atlas, U. S. Geol. Surv.

² For the Jurassic of the Pacific coast, see Hyatt, Bull. Geol. Soc. of Am., Vols. III and V, both articles chiefly paleontological; Meek, Paleontology of California, Vol. I, and the California folios of the U. S. Geol. Surv.

ern British Columbia, where the Lower and Middle Jurassic beds have little representation, the sea extended farther east than during the earlier part of the period. The deposits embrace all the usual sorts of sedimentary rocks, as well as considerable beds of fragmental igneous rock. Jurassic formations are also known at somewhat widely separated points in Alaska.¹ On the shores of Cook Inlet, 10,000 feet of Middle and Upper Jurassic are reported.

Thickness. The total thickness of the system in California does not exceed 2,000 feet (in part tuff). Farther east, in western Nevada,² nearer the land whence sediment was derived, it attains a thickness twice or thrice as great, being made up of limestone below, and slates above. In the western interior, its thickness is relatively slight.

Surface distribution and position of beds. The Jurassic beds do not now appear at the surface over large areas, being concealed in many places by younger beds. In some areas they retain their original position, while in others they have been tilted, or even folded or metamorphosed. This is especially the case in the Sierra Mountains and in some other ranges near the western coast.

CLOSE OF THE JURASSIC

Orogenic movements. At the close of the Jurassic period, there were considerable disturbances in the western part of North America. Great thicknesses of Triassic and Jurassic strata began to be folded into the Sierras,³ and the Cascade and Klamath⁴ Mountains farther north perhaps began their growth. It is not to be understood that these mountains attained great height at this time, or that they have not had later periods of growth. In the Klamath Mountains, for example, there are deformed beds of late Tertiary age. After this closing-Jurassic period of orogenic movement, the coast was

¹ See Alaskan Reports, U. S. Geol. Surv.

² King, Survey of the 40th Parallel, Vol. I.

³ Whitney, Geology of California, Vol. I, and Am. Jour. Sci., Vol. XXXVIII, 1864; and Fairbanks, Am. Geol., Vol. IX, 1892, Vol. XI, 1893.

⁴ Diller, Bull. Geol. Soc. Am., Vol. IV, p. 224, and 14th Ann. Rept., U. S. Geol. Surv.

somewhat farther west than now in northern California and southern Oregon.

It is probable that the Coast Range of California began its history at the close of this period, for deformed Jurassic beds (Golden Gate series) underlie the Lower Cretaceous unconformably in the axis of the range;¹ but the movements which gave the Coast Range its present form (modified by erosion), took place much later. Various other ranges of the west are thought to have begun their history as mountains at about the same time.

Toward the close of the period, much, if not all, of the great Upper Jurassic gulf of the northwestern part of the continent disappeared. All in all, the deformations at this time were greater than those which mark the close of most periods.

FOREIGN JURASSIC

Europe. Jurassic strata are exposed in many and widely separated parts of Europe, though for the most part in small areas only. As in the case of older systems, the present distribution of the system at the surface is no measure of its real extent.

It has been thought that the Jurassic of England is probably continuous with that of France beneath the English Channel, and thence by way of southeastern France, with those parts of the system which appear about the Mediterranean, and by way of Belgium, the Netherlands, and the German lowlands, with those parts which appear in Poland and Russia. In southern Russia, too, the Jurassic beds are probably wide-spread beneath younger formations. The lower part of the system is less extensive than the Middle, and the Middle less wide-spread than the Upper. Progressive submergence was, indeed, one of the features of the period. In this respect, the North American and European continents are in harmony, but marine formations are much more extended in Europe.

In Europe, the subdivision of the system has been carried to a high degree of refinement, but the many zones are grouped into a few principal divisions:

¹ Fairbanks, *Jour. Geol.*, Vol. III, pp. 415-430, and Smith, *Bull. Geol. Soc. of Am.*, Vol. V, pp. 257-258.

England (4,000–5,000 feet)

Upper (Portland) Oölite

Middle (Oxford) Oölite

Lower (Bath) Oölite

Lias

Germany (2,000–3,000 feet)

Upper (White) Jura or Malm

Middle (Brown) Jura or Dogger

Lower (Black) Jura or Lias

Among the more distinctive features of the system in Europe are the following:

(1) A considerable content of coal in some places, notably Hungary. (2) The abundance of oölitic limestone, both in England and on the continent. (3) The presence of lithographic stone (Solenhofen limestone of southern Germany). This stone is so fine and so even-grained, and at the same time so workable and so strong, that it has come into use the world over for lithographic purposes. The stone is also remarkable for the perfection of its fossils, including such delicate parts as the gauzy wings of insects. (4) The considerable development of non-marine beds in the lower part of the system, and again at its very top, especially outside of southern Europe.

Close of the Jurassic in Europe. The close of the Jurassic appears to have been marked by a somewhat wide-spread emergence of land. In central Europe, the emergence appears to have begun before the close of the Jurassic, for the latest beds (Purbeck) of the system in England are unconformable on beds lower in the system. Similar changes are known to have occurred in late Jurassic time in some other regions. On the other hand, the Upper Jurassic and the Lower Cretaceous beds are in places so closely associated as to show that no change of continental dimensions brought the Jurassic period to a close. Great deformative movements seem to have affected no part of Europe at the close of the period.

Extra-European Jurassic

The Upper Jurassic is wide-spread in *Arctic lands*. This distribution points to a great Arctic sea in the later part of the period, with two considerable dependencies to the south,—the one in Russia, the other, as we have seen, in western America. The Lower Jura is wanting in these latitudes, so far as known, and the Middle Jura is present but rarely.

The lower Jura occurs in southwestern *Asia* and *Japan*. The Middle Jura, largely elastic and of terrestrial origin, is wide-spread in Northern Asia, and marine in Middle Jura is known in northern India. The Upper Jura is much more extended, especially in the north. The system is known in *New Zealand*, *Borneo*, and *Australia*, and is well developed in *Mexico*, *Peru*, the *Bolivian Andes*, *Chile*, and *Argentina*.

Coal. Coal of considerable value is somewhat widely distributed in the Jurassic system. Besides that in the Lias of Hungary, coal occurs in the Caucasian region, Persia, Turkestan, southern Siberia, China, Japan, and Farther India, in many of the islands southeast of Asia, and in Australia and New Zealand. In the last-named island, the coal-bearing formations are interbedded with marine strata, suggesting considerable oscillations of level. In most of these countries, the coal is Liassic. Outside of North America, it is probably that no other system except the Pennsylvanian contains so much coal.

Climate

The testimony of fossils gathered in various parts of the world is to the effect that the climate of the Jurassic period was genial. In Europe, corals lived 3,000 miles north of their present limit, and saurians and ammonites flourished within the Arctic circle. Nevertheless, climatic zones were probably defined. Corals are unknown in the deposits of the great Arctic belt of Upper Jura, and the detailed study of the Jurassic faunas has led to the belief that one climatic zone is recorded in the Jurassic beds of the Arctic belt, a second in the deposits of central Europe, and a third in the southern province of Europe and the lands farther south. There can be no doubt of the differences in the faunas of these different provinces, but it is not certain that the differences were due wholly or even mainly, to climatic influences.

THE LIFE OF THE PERIOD

As the Jurassic was a period of sea extension, the marine life again assumes a place of leading importance. At the same time the land life, though suffering somewhat by the limitation of its

habitat, was favored by the genial climate. The frequent shiftings of land- and sea-areas, without involving great relief or severe climatic states, favored biological changes.

The Marine Life

It will be recalled that an expansional stage of epicontinental sea life set in toward the close of the Trias. This continued into the Jurassic, reaching a climax late in the period, when the sea attained the limit of its transgression over the land. The faunal progress is less well revealed in North America than in Europe and Asia, and the following general sketch of the life is based, in part, on the fossils of those continents.

The great features of the marine life of the period lay in (1) the continued dominance of ammonites among the invertebrates, (2) the rise of the belemnites, (3) the abundance and modernization of pelecypods, (4) the rejuvenation of corals and crinoids, (5) the marked development of sea-urchins, (6) the introduction of crabs and modern types of crustaceans, (7) the prevalence of foraminifera, radiolarians, and sponges, (8) the change in the aspect of the fishes, and (9) the great sea-serpents, descended from the land-reptiles of the Trias.

(1) The ammonites were still the masters among invertebrates, and were represented by many beautiful forms (Fig 481). They deployed along ascending lines in some cases, and retrograde lines in others. Erratic and degenerate developments showed themselves by uncoiling and strange coiling, presaging a stage of "sporting" and retrogression in the next period, followed by extinction. Despite these adverse foreshadowings, the ammonities were yet in the heyday of their luxuriance and beauty.

(2) Ammonites and their predecessors (ceratites, goniatites, and orthoceratites) were *tetrabranchs*, with external shells; but *dibranchs*, with internal shells, had appeared in the Trias, and rose rapidly to prominence in the form of *belemnites*, usually represented in the fossil state by their internal shell or "pen" (Fig. 482). In the course of the period the belemnites almost came to rival the ammonites, and were almost as characteristic of the successive

stages of deposition. The first known cuttle-fishes (sepeoids), also appeared at this time.

(3) Pelecypods flourished during the period (Fig. 483), and took on a markedly modern aspect, the oyster family taking the lead. Gastropods were abundant in some quarters, but singularly absent in others. Existing genera were represented.

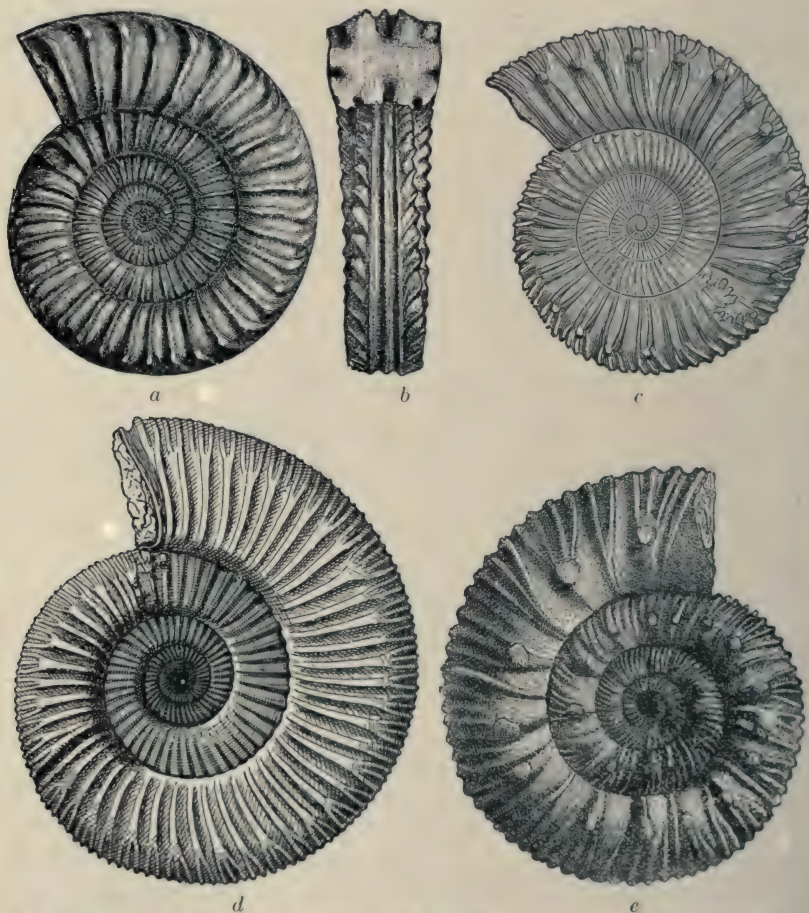


Fig. 481.—A GROUP OF JURASSIC AMMONITES. *a-b*, *Coroniceras bisulcatum* (Brug.), a lateral and ventral view of one of the *Arietidae*; *c*, *Deroceras subarmatum* (Young); *d*, *Perisphinctes tiziani* (Oppel); *e*, *Reineckia brancoi* Steinm.

(4) Suggestive of shallow clear seas was the reappearance of corals and crinoids in abundance in the later part of the period. The modern (*Hexacoralla*) type of corals was in the ascendant (*a, b, c*, Fig. 484), and formed abundant reefs, particularly in the European

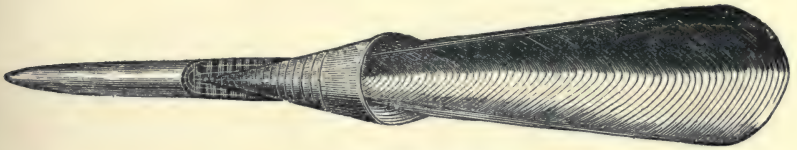


Fig. 482.—The internal shell of a belemnite, restored; the lower, solid, conical portion, (at the left in the Fig.) the part most frequently preserved, is the rostrum or guard; the middle portion is the phragmocone, which is a diminutive chambered shell with septa, siphuncle, and protoconch as in the older tetrabranch order; the upper part is the prostracum, which corresponds to the "pen" of the living cuttle-fish.

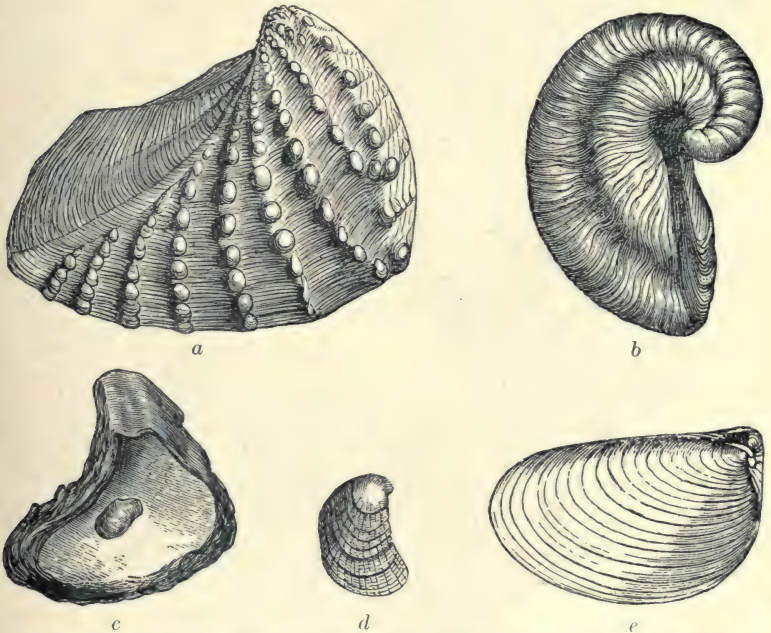


Fig. 483.—A GROUP OF JURASSIC PELECYPODS. *a*, *Trigoni navis* Lam.; *b*, *Gryphaea arcuata* Lam.; *c*, *Ostrea deltoidea* Sby.; *d*, *Exogyra* (*Ostrea*) *virgula* D'Orb.; *e*, *Aucella mosquensis* Keys.

seas of the Middle Oölitic stage. Crinoids also rose again to prominence, though their diversity was not great. They departed from Paleozoic forms in various ways. Most of them lived in shallow water, as most of the Paleozoic types had; but there is evidence

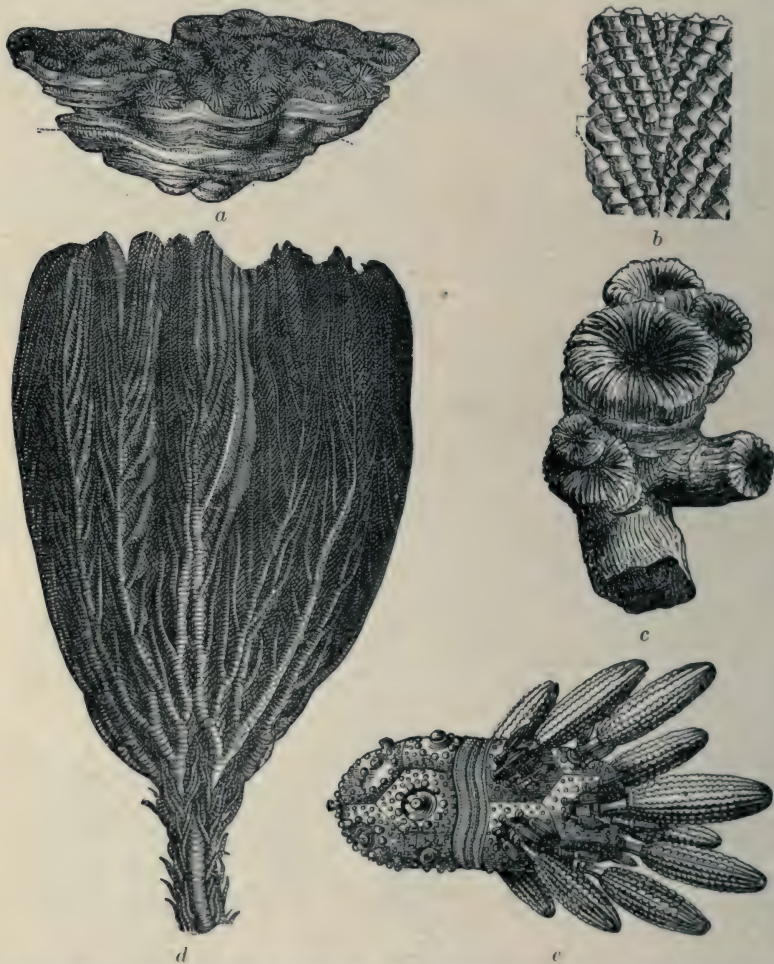


Fig. 484.—JURASSIC CœLENTERATA AND ECHINODERMATA. a and b, *Thamnastrea prolifera* Becker, a complete corallum, and the lateral surface of a costal septum, enlarged; c, *Thecosmilia trichotoma* (Goldf.); d, *Pentaclinurus briareus* Mill; e, *Cidaris coronata* Goldf.

that deep-water species had begun to appear, leading toward the prevalent but not exclusive habit of the present.

(5) The slow evolution of the sea-urchins in the Paleozoic era was succeeded in the late Trias by the beginning of a rapid evolution, which reached its climax in the early Tertiary.

(6) The Paleozoic crustaceans, the trilobites in the sea, and the eurypterids in the land waters, had been succeeded by the decapods which rose to a moderate and prolonged ascendancy. The prawns

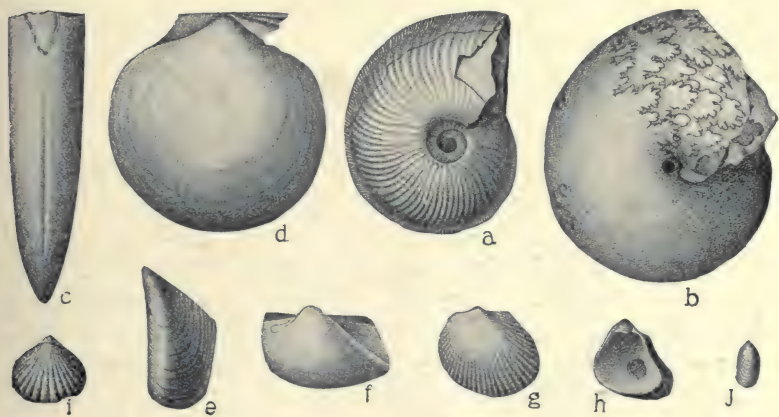


Fig. 485.—JURASSIC FOSSILS. *a-c*, Cephalopods: *a*, *Cardioceras cordiformis* M. and H.; *b*, *Neumayria henryi* M. and H.; *c*, *Belemnites densus* M. and H. *d-h*, Pelecypods: *d*, *Camptonectes bellistriatus* Meek; *e*, *Mytilus whitei* Whitf.; *f*, *Grammatodon inornatus* M. and H.; *g*, *Pseudomonotis curta* (Hall); *h*, *Ostrea strigilecula* White. *i* and *j*, Brachiopods: *i*, *Rhynchonella gnathophora* Meek; *j*, *Lingula brevirostra* M. and H.

and lobsters (*Macrura*, long-tailed decapods) were the earlier division, and the most numerous in this period; but the first of the known crabs (*Brachyura*, short-tailed decapods) appeared before the period was past. The macrurans seem to have frequented embayments and protected locations near the land, or perhaps within it, where terrestrial, fresh-water, and marine species are preserved in the same sediments. It is not improbable that the macrurans, then as now, had representatives in terrestrial waters, as well as in the sea.

(7) Sponges and foraminifera were prolific and are well preserved.

(8) A marked change in the aspect of the fishes had set in during the Trias, and was carried farther in this period. The cross-opterygians (Fig. 486) and dipnoans were reduced; the selachians continued undiminished; the skates and rays began their modern career; the *Chimæridæ*, the existing family of sea-cats or spook-fishes, made its appearance, so far as fossils show, and developed notably (Fig. 487); the forebears of the living garpikes and sturgeons took precedence in numbers; the forerunners of the modern *Amia* (Fig. 488) were important, and the initial forms of the bony fishes (teleosts), the dominant existing type, made their appearance. The aspect of the class was markedly more modern than at the close of the Paleozoic.

(9) It was noted under the Trias that certain land-reptiles went down to sea, and introduced a new phase of vertebrate mastery over the deep. Though doubtless suffering from the new dynasty, it appears that the fishes continued in notable abundance and variety. It will be seen later that they outlived the invading race, and resumed, in large measure, their former dominance. Some of the reptiles which had taken to the sea had become extinct, while others made their first appearance late in the period. The *ichthyosaurs* (fish-like saurians) reached their highest development in this period, and seem to have swum every sea. Their adaptation to aquatic life is shown in the complete transformation of their limbs into paddles (Fig. 489), in the reduction of the outline of the body to ichthic lines and proportions, in the sharp down-bending of the vertebræ at the end of the tail for the support of a caudal fin, in the long snout set with teeth adapted to seize and hold slipping prey, but not to masticate it, in the protection of the eye by bony plates, and, interestingly enough, in the development of a viviparous habit that freed them from the necessity of returning to land to deposit their eggs, after the manner of sea-going turtles and crocodiles. That their food consisted in part of invertebrates is evident from the fossil contents of the stomachs, the remains of 200 belemnites having been found in a single one. There were small as well as large forms of ichthyosaurs, some exceeding 30 feet in length.

Descended from a different stock, the *plesiosaurs* adapted them-

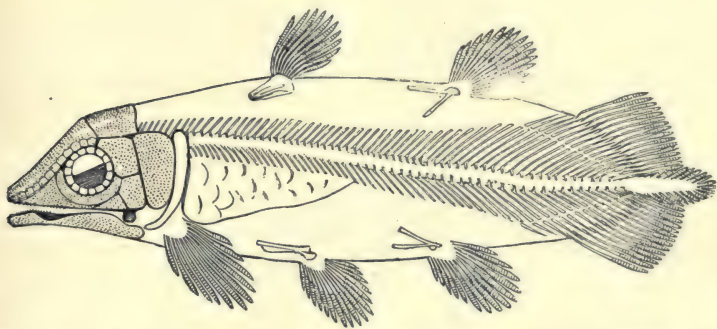


Fig. 486.— A Jurassic coelacanth, *Undina gulo*, a crossopterygian, about $\frac{1}{4}$ natural size; the outline of the air-bladder is shown just back of the gills and under the axis. (Restored by A. Smith Woodward.)

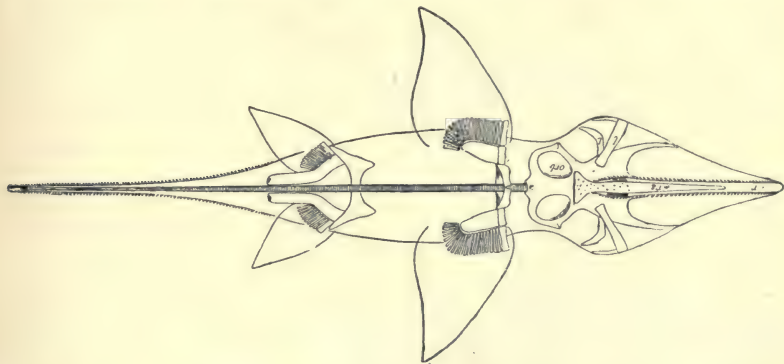


Fig. 487.— A Jurassic spookfish or chimæroid, *Squaloraja polyspondylo*, $\frac{1}{4}$ natural size; from the Lower Lias, Dorsetshire. (Restored by A. Smith Woodward.)

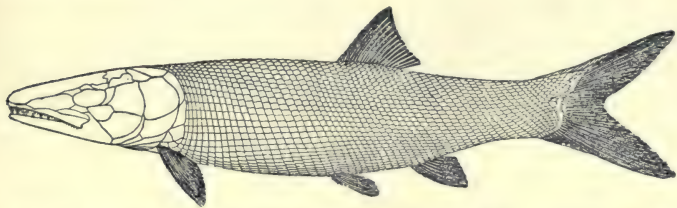


Fig. 488.— A Jurassic forerunner of the modern *Amia*, *Eugnathus athostomus*, about $\frac{1}{4}$ natural size, from the Lower Lias, Dorsetshire. (A. Smith Woodward.)

selves to sea life in another way (Fig. 490). The body took on a form like that of a turtle, while the neck was elongate, giving rise to the epigrammatic description "the body of a turtle strung on a



Fig. 489.—Outline and skeleton of *Ichthyosaurus quadriscissus*. (After Jaekel.)

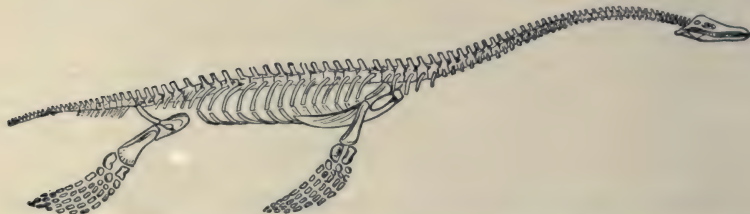


Fig. 490.—Skeleton of *Plesiosaurus dolichodeirus* Conyb. (Restored by Conybears.)

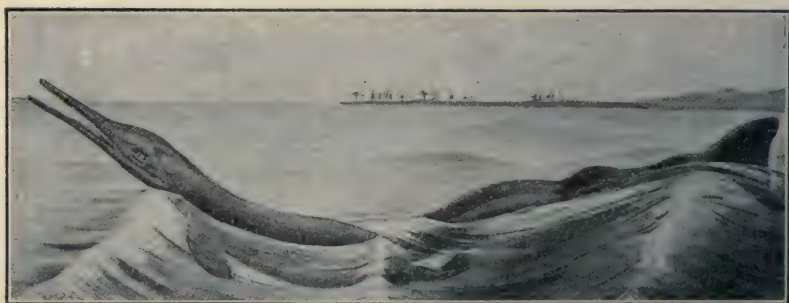


Fig. 491.—Restoration of a Jurassic crocodilian, *Geosaurus suevicus*. (Fraas.)

snake." Locomotion seems to have been chiefly dependent on the paddles, though a fin-like adaptation of the tail existed in some. The elongation of the neck was variable, the vertebræ of the neck

ranging from 13 to 76. The neck appears not to have been so flexible as familiar illustrations have represented it, nor were the jaws separable and extensible as in the case of snakes. This implies either that they lived on small prey, or tore their food to pieces before swallowing. They were doubtless formidable foes of the smaller sea animals, but probably not of the larger. Like the ichthyosaurs, they were without scales. They ranged from 8 to 40 or more feet in length.

Marine *crocodilians* made their appearance in the later part of the period. They had undergone a remarkable adaptation to the sea (Fig. 491). They were fish-like in appearance, their skins were bare, and their tails terminated in a large fin like that of the ichthyosaurs. The fore limbs were short and paddle-like. The hind limbs were modified but slightly from the land type, perhaps due to the recurring necessity of visiting the shores for depositing and hatching their eggs.

Marine turtles, so characteristic of the Cretaceous, had not yet appeared.

The Land Life

Vegetation. The land vegetation of the Jurassic was little more than a continuation and expansion of that of the late Triassic, with slow progress toward living types. Cycadeans, conifers, ferns, and equisetes were the leading plants, slightly more modernized than their Triassic ancestors, but not changed radically.¹ The cycadeans (*Bennettitales* and *Cycadales*) were perhaps the most distinctive forms, though the conifers showed the more notable modernization. They embraced yews, cypresses, arbovitae, and pines, all of which had a somewhat modern aspect, though all the species are extinct. The ginkgos also played a somewhat important role.

An interesting feature of the European record is the rather frequent occurrence of land plants in marine beds, which implies that many trunks, twigs, leaves, and fruits, were floated out to sea, and that the landward edges of the marine deposits have escaped

¹For a comprehensive paper on the Jurassic plants of the United States, with descriptions and illustrations by Lester F. Ward, see 20th Ann. Rept., U. S. Geol. Surv., 1898-99, pp. 334-430.

destruction. In the same beds are the remains of many land insects, not a few of them being wood-eating beetles.

In the closing stages of the period, the area of land was extended. This should in itself have been favorable to an expansional development of plants; but extensions of land are so liable to be attended by adverse climatic and topographic changes, that no safe inference can be drawn except from the actual record, which, in this case, is rather scanty.

Animals. Of the North American land faunas of the Jurassic, except perhaps its latest stages, little is known. But with the close of the period there appeared in the Morrison beds (p. 705) a rich but not varied land fauna, composed chiefly of dinosaurs. These animals attained remarkable size and diversity, and were easily lords of the reptile horde. Some were large, and some were small, and the group, as a whole, developed great diversity in many directions. There were not only carnivorous types, which had appeared in the Triassic, but numerous herbivorous forms. Among them all there was not a single type which was distinctively North American. It is therefore concluded that there was freedom of migration between the eastern and western continents at this time.

Of the carnivores, one of the most typical was *Ceratosaurus nasicornis* (Fig. 492). The fore limbs seem to have been used chiefly for seizing and holding prey, rarely for walking. The animal's pose was facilitated by hollow bones. The head was relatively large, an unusual character for a race among which small heads and brains were the fashion of the time. Not all the carnivorous dinosaurs were large. There were small leaping forms (like *Compsognathus*) not larger than a rabbit.

The herbivorous dinosaurs are known first in this system, but their development was so extraordinary that they soon outranked the carnivorous forms in both size and diversity. The *sauropoda* were generally massive, with sub-equal limbs and the quadruped habit. Among them, *Brontosaurus* (*Apatosaurus*) attained the extraordinary length of 60 feet and possibly more, taking rank as one of the largest of known land animals (Fig. 493). This enormous creature was characterized by weakness rather than strength, for its general organization was unwieldy, its head small, and its

brain had less diameter than its spinal cord. "The task of providing food for so large a body must have been a severe tax on so small a head." The largest of all known dinosaurs was *Brachiosaurus*, of which the femur measured more than two meters in length

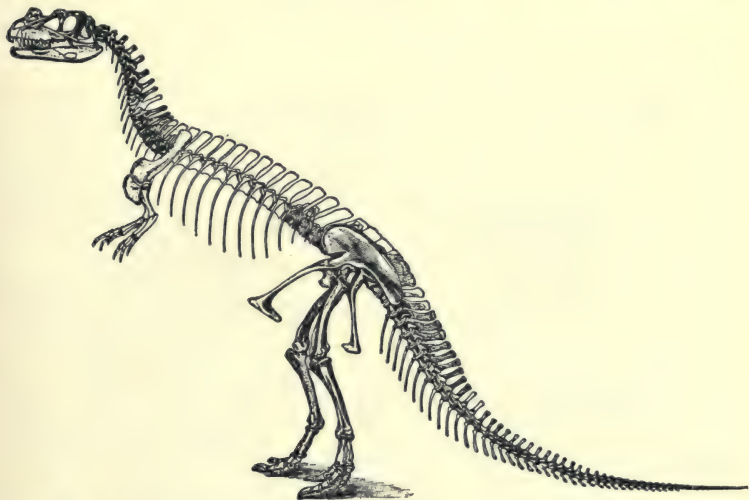


Fig. 492.— A carnivorous dinosaur, *Ceratosaurus nasicornis*, about $\frac{1}{40}$ natural size, i. e., length about 17 feet; from the Como beds, Colorado. (Restoration of skeleton by Marsh.)

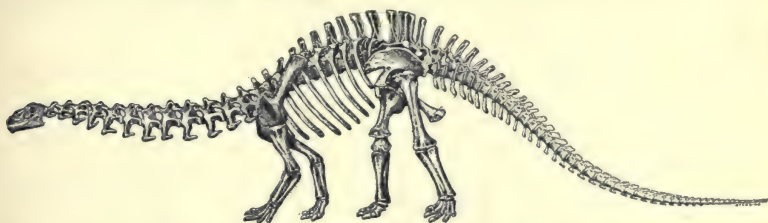


Fig. 493.— An herbivorous dinosaur, *Brontosaurus* (*Apatosaurus*). Restoration of skeleton by Riggs, nearly 60 feet long; from Wyoming.

(80 $\frac{1}{2}$ inches)¹. There were several other genera of similar nature, and of bulk only inferior to these monsters.

The typical *ornithopod* (bird-footed) *dinosaurs* were bipedal in habit, like the carnivores. On the hind limbs there were usually

¹ Riggs, Amer. Jour. Sci., 1903.

only three functional toes, so that they left a bird-like track; the fore limbs, however, had five digits. *Camptosaurus*, one of the largest of this group, measured about 30 feet in length, and 18 in height in the walking posture.

The *stegosaurus* were quadrupedal in habit, and had solid bones. They were curiously armored, and formed a very remarkable group



Fig. 494.—*Stegosaurus*, an armored dinosaur of the Jurassic. Interpreted by Charles R. Knight. (Lucas' *Animals of the Past*. By permission of the publishers, Messrs. McClure, Phillips & Company.)

that frequented England and Western America. They were not so large as some of the preceding, but found compensation in protective plates, spines, and similar modes of defense. The *Stegosaurus* of Colorado and Wyoming (Morrison beds) was one of the most unique (Fig. 494). Its diminutive head and brain imply a sluggish, stupid beast, depending for protection on its bulk and armor.

Turtles, which had lived elsewhere since the Middle Trias, made their first appearance in North America in the Morrison beds, and the *crocodilians* of the period, though still retaining the primitive

type of biconcave vertebræ, became differentiated into several branches. Primitive lizards were doubtless abundant, but because of their terrestrial habits and small size, they have little representation among the fossils, and none have been found in our continent.

It has already been noted that crowding on the land may have led some land reptiles to take to the sea. The same influence may have forced others to take to the air, thereby escaping the monsters of the swamps, jungles, and forests. Whatever the cause, a unique feature of the period was the development of *pterosaurs*, or flying



Fig. 495.—*Rhamphorhynchus phyllurus*, a flying saurian. (Restored by Marsh.)

reptiles. Appearing at the very close of the Trias in a few yet imperfectly known forms, they presented themselves at the opening of the Jurassic period as fully developed flying animals (*Dimorphodon*), and later formed a diversified group embracing long-tailed (as *Rhamphorhynchus*, Fig. 495) and short-tailed forms (as *Pterodactylus*, Fig. 496). With little doubt they sprang from some agile, hollow-boned saurian, more or less remotely akin to the slender, leaping dinosaurs. Between the ponderous brontosaurus (Fig. 493) and the pterosaurs (Fig. 495), the Jurassic saurians present the strangest contrasts.

The Jurassic pterosaurs were small, but their successors attained a wing-spread of nearly a score of feet. They were curiously composite in structure and adaptation. Their bones were hollow, their fore limbs modified for flight, their heads bird-like, and their jaws set with teeth, though toothless forms appeared later. They were

provided with membranes stretched, bat-like, from the fore limbs to the body and hind limbs, and serving as organs of flight (Fig. 495). The fifth, or as some paleontologists believe, the fourth, digit was greatly extended, and served as the chief support for the wing-membrane. The sternum was greatly developed, implying true powers of flight, a conclusion supported by the occurrence of their



Fig. 496.— Skeleton of pterodactyl, *Pterodactylus spectabilis*, from the lithographic stone at Eichstadt, Bavaria; about $\frac{3}{4}$ natural size. (After H. v. Meyer.)

remains in marine sediments free from other land fossils. Some of them had singular elongate rod-like tails, with a rudder-like expansion at the end.

The pterodactyls (Fig. 496) had short tails, and were usually small and slender. Fully differentiated as first found, the pterosaurs underwent no radical change of structure during their career, and the steps of their remarkable evolution are for the most part unknown. Representations of flying reptiles among the Jurassic fossils of North America are extremely rare.

A less bizarre, but really greater evolution, was the contemporaneous differentiation of true *birds*. The remote ancestors of the pterosaurs and the birds may have been closely allied, but there is no evidence that the birds are descended from pterosaurs. The two



Fig. 497.— The earliest known bird, *Archæopteryx macrura*. The long vertebrated tail, the clawed digits of the fore limbs, and the toothed jaws are ancestral features to be specially noted. (H. von Meyer.)

types are examples of analogous and parallel evolution, not of relationship.

The oldest known bird, *Archæopteryx macrura* (Fig. 497), shows an advanced state of evolution, and at the same time clear traces of reptilian ancestry. From this ancestry it retained a long, vertebrated tail, reptile-like claws, fore limbs, teeth set in sockets, biconcave vertebrae, and separate pelvic bones. On the other hand, its head and brain were bird-like, its anterior limbs adapted to flying in bird- (not pterosaurian) fashion, its posterior limbs modified for bird-like walking, and most distinctive of all, it was clothed with feathers. The development of the feathers, while yet the body retained so many reptilian features, is most notable. But for their fortunate preservation, it is uncertain whether the creature would have been classed as a bird or reptile. The known specimen was somewhat below the size of a crow.

The marvelous deployment of aquatic and terrestrial reptiles and of birds makes the scanty record of the *mammals* all the more singular. Only a few jaw bones of the size of those of mice and rats have been found. These low types are referred, without complete certainty, to marsupials. They appear to have been insectivorous.

The insects of the Jurassic appear to have included members of nearly all the fossilizable groups that were not dependent on angiospermous plants.

Map work. Folios published by the U. S. Geological Survey, good for the study of the Jurassic and Triassic systems, are the following: *California*, Downieville, Jackson, Pyramid Peak, Redding, San Luis; *Colorado*, Anthracite-Crested Butte, Rico, Telluride, Tenmile, Walsenburg; *Massachusetts-Connecticut*, Holyoke; *Montana*, Fort Benton; *New Jersey*, Passaic; *New York-New Jersey*, New York City; *Oregon*, Roseburg; *South Dakota-Nebraska*, Oelrichs; *Virginia-West Virginia-Maryland*, Harpers Ferry; *Wyoming*, Aladdin, Cloud Peak-Fort McKinney, Devils Tower.

These folios may well be grouped geographically for study. Thus those which deal with the Newark series of the east form one unit, those of the Rocky Mountains another, those of the Pacific coast another.

In the folios, the Jurassic and Triassic are commonly grouped together under the name Jura-Trias, but the text of the folios often separates the Jurassic from the Triassic, even where the map does not.

CHAPTER XXV

THE COMANCHEAN (LOWER CRETACEOUS) PERIOD¹

Introductory

The history of the Cretaceous period, as formerly defined, was complex. At its beginning, the larger part of the North American continent was above the sea. During its progress, the sequence of events in our continent was somewhat as follows: (1) A somewhat wide-spread warping of the continental surface, resulting in extensive submergence in Mexico and Texas, and a lesser submergence along the Pacific coast. At about the same time the Atlantic and Gulf coasts and some parts of the western interior were brought into such an attitude as to become sites of deposition, though not submerged. A prolonged period of sedimentation followed. (2) The period of sedimentation was followed by other geographic changes which inaugurated a prolonged interval of erosion which affected the recent deposits as well as older formations. (3) Later, the sea encroached upon the Atlantic and Gulf borders, extending somewhat beyond the non-marine formations of the earlier stage. It again covered Texas, and presently extended northward over the Great Plains, probably to the Arctic Ocean. On the Pacific coast, too, the sea gained on the land. Few greater transgressions of the land by the ocean are recorded in the long history of the North American continent. A long period of deposition was initiated by the submergence. It was succeeded by (4) a wide-spread withdrawal of the waters from the continent, leaving the land area nearly or quite as large as now.

The formations of the Cretaceous period, as outlined under (1) and (3) above, have been divided, commonly, into two main series, a Lower and an Upper. To the former were referred the deposits

¹ For a full review of the American Cretaceous, up to 1891, see White (C. A.), Bull. 82, U. S. Geol. Surv.

of the earlier and lesser submergence, and to the latter, those of the later and more extensive submergence. The distinctness of the Lower and Upper Cretaceous is however so great, that it seems more in keeping with the spirit of modern classification to regard them as separate systems, and the corresponding divisions of time as periods. What was formerly called the Lower Cretaceous series is here called the Comanchean system. The propriety of this classification is the more striking, since it is applicable to other continents as well as to our own.

FORMATIONS AND PHYSICAL HISTORY

The Atlantic and Gulf Border Regions

That part of the Comanchean system along the Atlantic coast is called the *Potomac*¹ series; the part along the eastern Gulf coast, where conditions of sedimentation appear to have been similar to those along the Atlantic, is the *Tuscaloosa*² series. The approximate surface distribution of these series is represented in Fig. 498, which shows that the system outcrops near the inland margin of the Coastal Plain. It is indeed the lowest member of the Coastal Plain group of formations. Neither the Potomac nor the Tuscaloosa series is believed to represent the whole of the period, and the two are not strictly contemporaneous.

Conditions of origin, and constitution. By the beginning of the Comanchean period, both the Appalachian Mountains and the area of the present Piedmont Plateau had been degraded well toward base-level, so that little warping of the surface appears to have been needed to convert portions of the coastal lands into sites of deposition, though more may have been necessary to provide lands high enough to furnish abundant sediments. The peneplanation of the eastern mountain and plateau region during the Jurassic period was no doubt attended by deep decay of the underlying

¹McGee, *Am. Jour. Sci.*, Vol. XXXV, 1888, pp. 120-143; Clark and Bibbins, *Jour. Geol.*, Vol. V, 1897, pp. 479-506, *Bull. Geol. Soc. Am.*, Vol. XIII, pp. 187-214; also reports of the Geological Surveys of New Jersey and Maryland, and folios of the U. S. Geol. Surv. covering parts of the Atlantic Coastal Plain.

²Smith, *Geol. Surv. of Ala.*, 1894.



Fig. 498.— Map showing the distribution of the Comanchean formations in North America. The conventions are the same as in preceding maps.

crystalline rocks, and the consequent accumulation of a heavy mantle of residuary, insoluble earth. The warping which inaugurated the Comanchean period seems to have involved a rise of the Appalachian tract, and a consequent rejuvenation of the drainage from it, while the coastward tract was left relatively flat, or so warped as to become a zone of lodgment for the sediments brought down by the quickened drainage from the west. Lakes, marshes, etc., were probably features of the lodgment area. These conditions are in harmony with the constitution of the deposits, which consist of gravel (or conglomerate), sand (or sandstone), and clay, largely uncemented.

The gravel at any point is made up principally of materials derived from formations adjacent on the west, and subordinately from subjacent formations. It is often arkose in the immediate vicinity of the feldspar-bearing crystalline rocks, but elsewhere it is composed chiefly of the resistant products of mature weathering.

The sands are sometimes fine and the grains well rounded, as if transported far by moving water, and sometimes coarse and angular, as if they had been subjected to but little wear. Locally they contain feldspar grains, or bits of kaolin which have resulted from their decay. The presence of the feldspar in the sand, like the presence of pieces of schist in the gravel, shows that erosion sometimes exceeded rock decay. This betokens high land to the west whence the sediments were derived, and is one of the reasons for the belief that the region west of the site of deposition was tilted upward at this time.

Beds of clay of such purity and magnitude are found in the Potomac series, that they have been extensively utilized, especially in New Jersey,¹ for the manufacture of clay wares. The clay often shows little stratification, and is notable for its bright and variegated colors, black, white, yellow, purple, and red being not uncommon. White is to be looked upon as the normal color; the others are the result of various impurities, the black being due to organic matter.

The clay, sand, and gravel are irregularly disposed, doubtless

¹ Cook, Report on Clays, Geol. Surv. of New Jersey, 1868, and Kummel, 1904.

the result of the physical conditions where the sedimentation took place, conditions which might have existed along the lower courses of rivers or at their debouchures, where shore-waters had little effect upon them.

In addition to the elastic sediment, there is a little lignite, and some iron ore, and though both are widely distributed, neither is of much commercial value.

Stratigraphy and stratigraphic relations. The Potomac and Tuscaloosa series are nearly horizontal, with a gentle dip seaward. The Potomac series rests unconformably on Triassic and other formations (Fig. 499), and the Tuscaloosa series on Paleozoic or

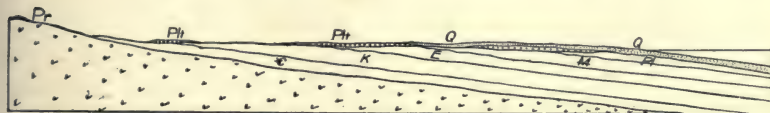


Fig. 499.—Section showing relations of various members of the Coastal series. C, Comanchean; K, Cretaceous; E, Eocene; M, Miocene; Pl, Pliocene; Q, Quaternary.

older strata. Both series are overlain unconformably by the Upper Cretaceous.

Thickness. The Potomac series rarely reaches a thickness of 700 feet. The thickness of the Tuscaloosa series is about twice as great.

*The Texas Region*¹

The Comanchean system is more fully represented in Texas than farther east, but its stratigraphic relations are the same. The beds appear at the surface over an area distant from the coast, dip seaward at a low angle, and are concealed near the coast by younger formations. The system includes three distinct series, (1) the Trinity, (2) the Fredericksburg, and (3) the Washita. The first was perhaps contemporaneous with the Potomac series; and the last is probably younger than any part of the system on the Atlantic coast. The system here is much thicker than farther east, ranging from 1,000 feet to about 4,000. Some parts of it are marine, and

¹ Hill, 21st Ann. Rept., U. S. Geol. Surv., Pt. VII, and Bull. Geol. Soc. Am., Vol. V, 1893, pp. 297-338. Also Hill and Vaughan, 18th Ann. Rept., U. S. Geol. Surv., Pt. II, pp. 217-237.

some terrestrial in origin. The marine part of the system includes much limestone.

From Texas, the Comanchean formations, or some of them, originally spread northward into Kansas,¹ northwestward to Colorado, and westward to Arizona. Though they appear at the surface in small areas only, their extent may be considerable beneath younger formations.

In Mexico. The Comanchean of Mexico is mainly limestone, and, though but imperfectly known, has been estimated to have the extraordinary thickness of 10,000 to 20,000 feet. Its distribution is such as to show that a large part of that country was beneath the sea. It has been conjectured that the waters of the Atlantic and Pacific mingled over the site of some part of Mexico at this time, but this is uncertain. If the oceans were connected, it was probably across southern Mexico, or perhaps Central America. At any rate, there does not seem to have been free faunal intermigration between the Gulf coast and the coast of California. In its abundance of limestone, the series of Texas and Mexico resemble the Lower Cretaceous of the northern part of South America, and southern Europe.

The Northern Interior

Though the sea is not known to have had access to the western interior of North America north of Kansas during the Comanchean period, elastic beds of terrestrial origin, which are perhaps Comanchean, are known at various points farther north. The beds in question, the Morrison,² Como, and Atlantosaurus beds, are best known along the Front Range through Colorado and Wyoming, and in the Black Hills,³ though they probably reach northward to Montana. If all the beds thought to be the equivalent of the Morrison, are really so, the formation is widely distributed. These beds are often regarded as late Jurassic,⁴ and this may be their proper classification.

In Montana, Alberta, and Assiniboia, there are beds (the Kootenai Prosser, "Comanchean Series of Kansas," the Univ. Geol. Surv. of Kans., Vol. II, 1897.

² Cross, Pike's Peak folio, U. S. Geol. Surv., 1894.

³ Ward, Jour. Geol., Vol. II, p. 250.

⁴ Knight, Bull. 45, Wyo. Exp. Station, p. 134.

may and Cascade formations,¹ etc.) similar in character to those just mentioned. They are mainly clastic, and contain some coal. Their fossils are mostly of plants of early Cretaceous types. In Montana, the Kootenay formation overlies the Morrison. The exact relations of these formations to the Comanchean of the Atlantic and Gulf coasts is not known.

To the Morrison and Kootenay formations a lacustrine origin has usually been assigned, and there is perhaps no adequate ground for questioning this conclusion for some parts of the formations; but the character of some of the beds and the nature and distribution of their fossils suggest a fluviatile origin for parts, and perhaps for large parts, of the series. The position of these formations with reference to the Rocky Mountain axis, is much the same as that of the Potomac series to the Appalachian axis, and a similar conception as to the mode of origin may be entertained.

The Pacific Border

In the United States. The Lower Cretaceous beds have great development in California, where they attain their maximum known thickness. They are known here as the *Shastan* group,² made up of the Knoxville series below and the Horsetown above. The deposits are thickest in the Sacramento valley, the sediments having been furnished by the newly uplifted mountains (p. 710). Most of the thick system, including its basal beds, bears the marks of a shallow-water origin. The *Shastan* group is represented in Oregon also.³

Where the base of the *Shastan* series has been observed, it is unconformable on Jurassic rocks, or on metamorphic rocks of unknown age. It is overlain unconformably in some places, and without apparent unconformity in others, by the (Upper) Cretaceous (*Chico*⁴ series). In the Coast Range of California, the system contains some igneous rock.

¹ Fort Benton, Mont. folio, U. S. Geol. Surv.

² Turner, Bull. Geol. Soc. Am., Vol. II; Diller, Am. Jour. Sci., Vol. XL, 1890, and Bull. Geol. Soc. Am., Vol. IV, 1892; Diller and Stanton, idem, Vol. V, a Summary for the Pacific Coast brought up to 1894.

³ Diller, Am. Jour. Sci., Vol. XXIII, 1907.

⁴ Fairbanks, Jour. Geol., Vol. III, pp. 415-430, and San Luis, Cal., folio, U. S. Geol. Surv.

The fauna of the Shastan group is markedly unlike that of the Comanchean of Texas, and since the differences do not seem referable to climate, it seems most rational to suppose a barrier to marine life between the two regions. In the United States, this barrier was perhaps wide; but in Mexico it was probably narrow, for the Comanchean fauna, or some part of it, extends west to the western part of Mexico, while farther south the Pacific fauna reached eastern Mexico. The exact position of the barrier which separated the oceans is not known. It is possible, on the other hand, to think of ocean currents of different temperatures, as determining the differences of faunas. Though the exact time relations of the Comanchean and Shastan series have not been determined, they are believed to be approximately equivalent.

North of the United States. Farther north, Lower Cretaceous beds (Queen Charlotte series) occur in the Queen Charlotte Islands,¹ where they have an estimated thickness of between 9,000 and 10,000 feet. In British Columbia, the coast line was east of the Coast ranges, and extended farther and farther east with increasing latitude, until the ocean swept clean across the site of the Cordilleras in the early part of the period, and extended south along the area which is now the east base of the mountains.² The Kootenay formation is perhaps partly contemporaneous with these marine beds. The Comanchean system of British Columbia generally rests unconformably on the Triassic system, and contains some volcanic material and, locally, coal.

Farther north, the Lower Cretaceous has not always been separated from the Upper, but the former has extensive development in some parts of northern Alaska,³ where it contains coal. It is also believed to occur on the west coast of Greenland, where the beds are believed to represent some such horizon as that of the Kootenay, or Potomac.⁴

¹ Dawson, *Geo. M., Am. Jour. Sci.*, Vol. XXXVIII, 1889, pp. 120-127.

² Dawson, *Science*, March 15, 1901; and *Bull. Geol. Soc. Am.*, Vol. XII, p. 87.

³ Professional Papers 15 and 20, U. S. Geol. Surv.

⁴ White and Schuchert, *Cretaceous Series of the West Coast of Greenland*, *Bull. Geol. Soc. Am.*, Vol. IX, pp. 343-368, 1898.

The Close of the Comanchean (Lower Cretaceous) period in North America

Considerable changes in the geography of North America brought the Comanchean period to a close. Along the Atlantic and Gulf borders considerable tracts were converted from areas of deposition into areas of erosion. The sea was withdrawn from Texas, and the Comanchean system somewhat deformed and faulted; in Mexico the deformation of the system was notable. Along some parts of the western coast, there was folding of the Lower Cretaceous beds,¹ accompanied by volcanic activity, as in the southern Coast Range of California, while in other places the sea spread itself over areas which had been land. Still other areas in the west appear to have emerged at this time, and never to have been submerged since.²

On the whole, the deformative movements at the close of the Comanchean period were more extensive than those which occurred in the midst of any one of the Paleozoic periods as now defined, if the Mississippian and Pennsylvanian are regarded as separate periods. The force of this point in its bearing on the distinctness of the Comanchean period from the Cretaceous, is increased by the fact that the latter was inaugurated by a notable submergence, affecting great areas. During this submergence, Cretaceous beds of marine origin were deposited on the eroded surface of the Comanchean system, somewhat generally, and the younger system overlapped the older in most regions where both are present. The reverse was the case, however, in British Columbia. On stratigraphic grounds, therefore, the distinctness of the two systems is clear. The case is hardly less clear on the paleontological side. In Texas, for example, no species of marine life is known to have lived over the time-interval recorded by the unconformity between the two systems.

¹ Fairbanks, Jour. Geol., Vol. III, pp. 415-430, and San Luis folio, U. S. Geol. Surv.

² Ransome, Bisbee, Ariz. folio, U. S. Geol. Surv.

THE LOWER CRETACEOUS IN OTHER CONTINENTS¹

Europe. The deposits in some of the lakes, marshes, estuaries, and other lodgment basins which resulted from the geographic changes at the close of the Jurassic period in Europe, record the transition from that period to the early Cretaceous. The interruption of marine sedimentation in Southern Europe was not so general, and over considerable areas the Lower Cretaceous succeeds the Jurassic conformably, both being marine. In Russia, it is difficult in many places, to define the upper limit of the Jurassic, so complete is the gradation into the (Lower) Cretaceous.

In Europe, as in North America, the Cretaceous, as that term is there used, is divisible into two major parts, a lower and an upper, as distinct as successive systems usually are. As in North America, the lower division is much more restricted in its distribution than the upper, and is, to a large extent, of non-marine origin.

During the initial stages of the Lower Cretaceous, the areas of sedimentation were more or less isolated; but later, advances of the sea enlarged some of these areas, and finally united many of them by bringing them beneath a common sea. The Lower Cretaceous formations embrace all sorts of clastic rocks, together with limestone, glauconitic beds, beds of coal (northwestern Germany), and iron ore. They embrace, indeed, about all varieties of sedimentary rock except chalk, the rock from which the name "Cretaceous" was derived. In southern Europe, much of the system is limestone.

Other continents. In other continents, the Lower and Upper Cretaceous have been less clearly differentiated; yet enough is known to show that the Lower and Upper Cretaceous systems are, in general, markedly different, both in origin and distribution. Lower Cretaceous formations of marine origin are wide-spread in Siberia, Japan, and the southern part of Asia, but in limited areas only in most other parts. The system is believed to have slight development in the mountain regions of northwestern *Africa*, where it is really an extension of the Lower Cretaceous of southern Europe

¹ The term Comanchean is not applied to the Lower Cretaceous formations outside of North America.

and is unconformable beneath the Upper Cretaceous, and in South Africa.¹ Marine Lower Cretaceous is wide-spread in the northern part of *South America*, but not elsewhere east of the Andes. It is generally absent about the borders of the South Atlantic. On the other hand, marine Lower Cretaceous beds occur in many places about the southern Pacific and Indian Oceans. The areas where the system is exposed are, however, mostly small.

Close of the period. Geographic changes of importance occurred in various parts of the earth at the close of the early Cretaceous period, and are recorded (1) in the unconformities between the Lower and Upper Cretaceous systems, as at some points in Europe, north Africa, Australia, and South America, and (2) in the differences in their distribution, as will appear in the account of the following system.

Climate. In the aggregate, the known fossils of the Lower Cretaceous of America are not such as to indicate great diversity of climate. Even in Greenland, the climate seems to have been as warm as that of warm temperate regions to-day.

The fresh-water fossils of those deposits of central Europe which represent the transition from the Jurassic to the Lower Cretaceous, are, on the whole, of such a character as to indicate a climate far from tropical. So far as they afford a warrant for inference, the climate of central Europe would seem to have been comparable with that of the temperate portions of America to-day. The fossils of lower latitudes denote a warmer climate. On the whole, European fossils seem to afford better evidence of the existence of climatic zones than those of America. From them paleontologists have thought to find warrant for the hypothesis that the climate underwent more or less fluctuation during the course of the period.

LIFE

The terrestrial vegetation. Fossil plants constitute the chief record of the life of the early stages of the Comanchean in America. The earliest flora was akin to that of the Jurassic, in that the cycas-

¹ Ann. Rept. Geol. Com. Cape of Good Hope, 1901, p. 38; Corstorphine, History of Stratigraphical Investigations in South Africa, Rept. S. Af. Assn. for Adv. of Sci., 1904; and Rogers, Geology of Cape Colony, 1905.

deans (Fig. 500), conifers, ferns, and horsetails were the dominant forms. In most of Europe, this group held possession of the land throughout the period, though angiosperms appeared in Portugal

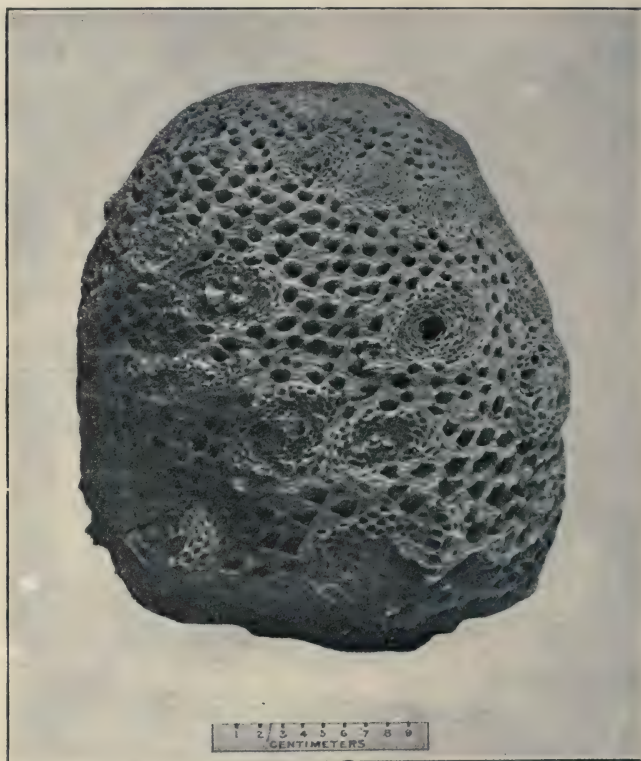


Fig. 500.—A cycadian trunk from the Black Hills, Dakota, *Cycadeoidea dakotensis* Ward, Lower Cretaceous. (Ward.)

before its close. Descendants of Jurassic types of plants also continued throughout the period in northwestern America.

The introduction of angiosperms. The eastern and central America angiosperms, including both monocotyledons and dicotyledons, appeared early in the period, and developed so rapidly that by the beginning of the next period they seem to have overrun the continent. This is one of the most radical evolutions in the

history of the plant kingdom. The precise time and place of origin of the angiosperms is not known, but present data point to the borders of the north Atlantic as the place of origin, and the late Jurassic or earliest Comanchean as the time.

About 400 species of Comanchean angiosperms are known from the Atlantic coast. They were in a minority in the lowest Potomac, but increase to an overwhelming majority in the upper beds. The earliest forms are ancestral, but not really primitive, and throw

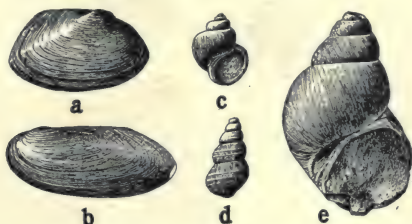


Fig. 501.— FRESH-WATER FAUNA OF THE COMANCHEAN (Lower Cretaceous) from Montana. *a* and *b*, *Pelecypods*: *a*, *Unio farri* Stanton; *b*, *Unio douglassi* Stanton; *c-e*, *Gastropods*: *c*, *Viviparus montanensis* Stanton; *d*, *Goniobosis* (?) *ortmanni* Stanton; *e*, *Campeloma harlowtonensis* Stanton. (Stanton.)

little light on the derivation of the group. The majority bear definite resemblances to modern genera and some (as *Sassafras*, *Ficus*, *Myrica*, and *Aralia*) are referred to living genera. Before the end of the period, figs, magnolias, tulip trees, laurels, cinnamon and other forms referred to modern genera, but not to modern species, had appeared. The cycadeans had dropped to an insignificant place, and the conifers and ferns, while not equally reduced, were subordinate to the angiosperms.

The land animals. The aspect of the vertebrate life was intermediate between that of the Jurassic and Upper Cretaceous, and, so far as it is known, has been sketched already (p. 720). Little is known of other forms of terrestrial animal life.

The fresh-water fauna. The molluscan fauna of the inland waters had assumed a pronouncedly modern aspect, as illustrated in Fig. 501. It had probably attained considerable importance through the extension of the fresh waters, but the record is by no

means so ample as would be expected if the deposits were made mainly in lakes and river channels. This is an additional reason for the growing opinion that the terrestrial deposits were in considerable part the products of land-wash of the more transient type, due to overflows, storm-wash, sheet-wash, and other forms of more strictly subaërial aggradation.



Fig. 502.—THE COMANCHEAN FAUNA OF THE TEXAN PROVINCE. *a-c*, Echinoids: *a*, *Holaster simplex* Shum.; *b*, *Diplopodia texanum* Roemer; *c*, *Hemister dalli* Clark. *d-h*, Pelecypods: *d*, *Anatina austinensis* Vaughan; *e*, *Homomya austinensis* Vaughan; *f*, *Trigonta emoryi* Conrad; *g*, *Lima wacoensis* Roemer; *h*, *Pecten texanus* Roemer. *i-l*, Gastropods: *i*, *Fusus texanus* Vaughan; *j*, *Turritella budaensis* Vaughan; *k*, *Cerithium* (?) *texanum* Vaughan; *l*, *Trochus* sp. *m*, a coral, *Parasmilia texana* Vaughan.

The marine faunas. Two very distinct marine faunas are found in North America, implying two distinct maritime provinces—that of the Mexican Gulf and that of the Pacific. The former had its connections eastward with Portugal and the Mediterranean region, the latter, northward and westward with Asia and Russia, though the boreal element is less conspicuous in the upper part (Horsetown). No species common to the two provinces is known. The decline of the boreal aspect of the western fauna may have been due to the closing of Bering Strait, thus shutting off cold currents from the Arctic.¹

¹ Stanton, Jour. Geol., Vol. XVII.

The Comanchean faunas are said to represent three distinct facies, the *reef* facies, most conspicuous, and the *littoral* and *deeper* water facies.



Fig. 503.— FAUNA OF THE SHASTAN SERIES, (chiefly Knoxville). *a-c* Cephalopods: *a*, *Lytoceras batesii* Trask; *b*, *Phylloceras knoxvillensis* Stanton; *c*, *Hoplites angulatus* Stanton. *d-h*, Gastropods: *d*, *Astresius liratus* Gabb; *e*, *Amberleya dillerti* Stanton; *f*, *Cerithium paskentaensis* Stanton; *g*, *Hypsipleura gregaria* Stanton; *h*, *Turbo moyonensis* Stanton. *i-q*, Pelecypods: *i*, *Pecten complexicosta* Gabb; *j*, *Corbula* (?) *persulcata* Stanton; *k* and *l*, *Aucella piochii* var. *orata* Gabb; *m*, *A. crassicollis* Keyserling; *n*, *Astarte californica* Stanton; *o*, *Arca tehamaensis* Stanton; *p*, *Nucula storrsi* Stanton; *q*, *Leda glabra* Stanton; *r*, *Rhynchonella whineyi* Gabb, a brachiopod. (After Stanton.)

CHAPTER XXVI

THE CRETACEOUS PERIOD

FORMATIONS AND PHYSICAL HISTORY

The Cretaceous period was ushered in, so far as North America is concerned, by a notable encroachment of the sea. In the United States, the system is found in (1) the Atlantic Coastal Plain; (2) the Coastal Plain of the Gulf, both east and west of the Mississippi; (3) the Great Plains, from the Gulf of Mexico to the Arctic Ocean; (4) at many points in the western mountains, and (5) over considerable areas along the Pacific coast. While the distribution of this system has much in common with that of the Comanchean, it is much more wide-spread (Fig. 504). Unlike the Comanchean, the system is chiefly marine.

*The Atlantic Border Region*¹

The Cretaceous beds come to the surface in a belt near the western margin of the Atlantic Coastal Plain, just east of the outcrop of the Potomac series (Fig. 504). The beds have been but little disturbed, and still dip, as when deposited, slightly to seaward, and in that direction pass beneath younger formations. The formations are chiefly of unindurated clay and sand, with not a little greensand marl, which is rather characteristic of the system. There is also some limestone.

The distinguishing constituent of the greensand marl is glauconite, primarily a hydrous silicate of potash and iron,² which occurs in grains. Glauconite is now making in some parts of the sea, and from the situations in which it is formed, it is inferred that

¹ Besides the State Reports referred to under the Comanchean, see Clark, Bull. Geol. Soc. of Am., Vol. I, 1897, pp. 315-358, and Weller, Jour. Geol., Vol. XIII, p. 71.

² Glauconite is usually impure, and, as it occurs in nature, contains several other ingredients.



Fig. 504.— Map showing the distribution of the Cretaceous formation in North America. The conventions are the same as in preceding maps.

the conditions necessary for its development are the following:¹ (1) Water of moderate depth, 100 to 200 fathoms being the most favorable; (2) a meager supply of land-derived sediment; and (3) the presence of foraminifera. The production of the glauconite seems to be effected by chemical changes induced in sediments perhaps as the result of decomposition of the organic matter contained in the foraminiferal shells. The abundance of greensand marl, which is not a common formation outside the Cretaceous, in corresponding systems of different continents, is one of the many striking inter-continental resemblances.

The aggregate thickness of the Cretaceous beds along the Atlantic coast nowhere exceeds a few hundred feet.

The subdivisions now generally recognized are the following, commencing with the lowest: 1. *Matawan* formation, 2. *Monmouth* formation; 3. *Rancocas* formation; 4. *Manasquan* formation.

These formations are not severally continuous throughout the coastal region. Thus the Matawan formation does not appear at the surface south of Maryland, being overlapped in that direction by later beds. All the formations show notable variations when traced along their strikes, and borings to the east of the outcrops show that they also vary seaward from their landward margins.

Though the beds have been but little changed since their deposition, certain alterations are worthy of note. The porous beds of greensand marl have been changed, locally, to brown, by the decomposition of the silicate and the formation of ferric oxide. Cementation, chiefly by ferric oxide, has indurated certain beds at some localities, and many of the conspicuous hills within the area of Cretaceous outcrops are due to a capping of this ironstone. The cemented layers are most likely to occur at the junction of formations of different texture, a generalization which holds in other partially indurated series.

The Eastern Gulf Border

The Cretaceous formations of the Eastern Gulf states appear at the surface some distance from the coast (Fig. 505), and dip

¹ For brief summary concerning the origin of greensand marl, see Clark, Jour. Geol., Vol. II, p. 161. For a fuller account, see Challenger Report on Deep Sea Deposits.

seaward at a low angle. Near the Mississippi, the belt of their exposure extends northward to Kentucky. If any of the formations once had greater extensions to the northward, as is probable, they have been worn away except for possible meager remnants, not certainly identified.

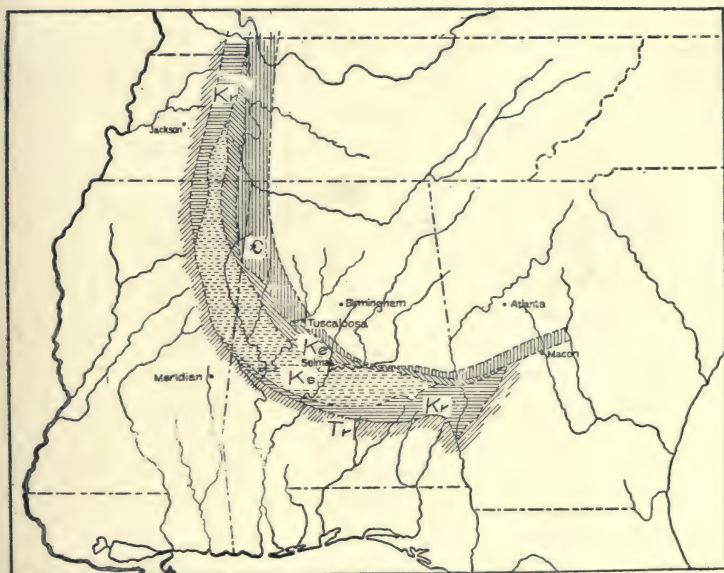


Fig. 505.—Map showing the positions of the several members of the Comanchean and Cretaceous systems in Alabama and adjacent states. *C*, Tuscaloosa series (Comanchean); *Ke*, Eutaw formation; *Ks*, Selma chalk; *Kr*, Ripley formation; *Tr*, Tertiary. (After Smith.)

In Alabama,¹ where the system is best known, there are three principal divisions: the *Eutaw* below (mainly clays and sands, some greensand, 300 feet), the *Selma Chalk* (*Rotten limestone*, 1,000 feet) in the middle, and *Ripley* (mainly sand, 200–500 feet) above. The *Eutaw* is believed to be the equivalent of the *Matawan* formation of the Atlantic coast, and the *Ripley* is thought to be older than the *Rancocas*.

¹ For an account of the Cretaceous of Alabama, see Smith, Report of the Alabama Survey for 1894. See also Safford, *Geology of Tennessee*, 1869, and Hilgard, *Geology of Mississippi*, 1860.

The Cretaceous beds of the Gulf coast (Alabama) have been disturbed rather more than the corresponding beds along those parts of the Atlantic coast where the system has been carefully studied. They have been bent into low anticlines and synclines in some places, and even faulted to a slight extent.

The Western Gulf Region¹

The general stratigraphic relations of the system here are the same as farther east, but deposition seems to have been well under way in Texas before the oldest beds of the system farther east were laid down. Alternating beds of sand, shale, limestone, and marl, most of which are of marine origin, make up the system. They attain a maximum thickness of about 4,000 feet. Three principal subdivisions are recognized:² (1) The *Dakota*; (2) the *Colorado*; and (3) the *Montana*.

The *Dakota* formation, 600 feet and less thick, is largely of sandstone, with some lignite, and is, for the most part, of non-marine origin. The *Colorado* series contains much limestone (or chalk) of marine origin. Its thickness is about 1,000 feet. The *Montana* series is more largely elastic, and from it the oil of the Corsicana oil field of Texas is derived. Locally, the system is much faulted. From Texas it is continued northward into Arkansas, and westward into New Mexico.

The Cretaceous of the western Gulf region differs from the corresponding system farther east, in its greater thickness, and in its greater proportion of calcareous matter, largely in the condition of chalk. Of limestone or chalk, the Cretaceous of the Atlantic coast contains little, that of the eastern Gulf region (Alabama and Mississippi) more, and that of Texas much; nor is the chalk confined to Texas, as will be seen.

The Western Interior

The Cretaceous system of the western interior consists of the following subdivisions, commencing at the bottom: 1. *Dakota*; 2. *Colorado* (including the Benton and the Niobrara formations); 3. *Montana* (including Ft. Pierre and Fox Hills); and 4. *Laramie*.

¹ Hill and Vaughan, 18th Ann. Rept., U. S. Geol. Surv., Pt. II, pp. 238-242.

² Hill, 21st Ann. Rept., U. S. Geol. Surv., Pt. VII, p. 114.

The Dakota formation. The Dakota formation, mainly of non-marine origin, is wide-spread in the Great Plains, though buried over the greater part of the area. It extends westward beyond the Rocky Mountains, though in the mountain region the area of deposition was interrupted by elevations which rose above the lakes, marshes, or river flats where the sedimentation took place. The formation is largely sandstone, though it contains much conglomerate and clay, and some lignite.

The formation was formerly regarded as lacustrine, but it is perhaps to be regarded rather as the joint product of subaërial and fluvial deposition. The presence of bird tracks in Kansas,¹ and the wide-spread abundance of fossil leaves of angiosperms, in a condition which precludes much transportation, imply subaërial sedimentation to a notable extent at least. The upper part of the formation carries some marine fossils. North of Texas the formation is in apparent conformity with the Comanchean in some places, though in others, as in the Wasatch and Uinta mountains, it rests on older formations.

The formation is an important source of water in the semi-arid plains. It takes in the water where it outcrops near the mountains and the water follows the beds down their dip to the eastward. Along the east base of the Rocky Mountains, where the beds have been tilted, the less resistant formations associated with this sandstone have been removed or worn down, leaving the outcropping edges of this formation as ridges or "hogbacks" (Fig. 120), characteristic of the east base of the Rocky Mountains much of the way from New Mexico to Canada.

The Colorado series.² The Colorado series records an extensive invasion of the western interior by the sea, the invasion going so far, probably, as to establish a connection between the Gulf of Mexico on the south and the Arctic Ocean on the north, over the site of the Great Plains. The western border of this sea appears to have been in Arizona, Utah, eastern Idaho, and western Montana, and the eastern as far east as Minnesota, Iowa, and Kansas. Clastic

¹ Williston, Univ. of Kans. Geol. Surv., Vol. IV, p. 50.

² For subdivisions of this series, see Logan, Jour. Geol., Vol. VII, pp. 83-91, and folios of the U. S. Geol. Surv.

formations predominate in the Colorado series as a whole, but there are beds of chalk comparable to those of Europe, in Texas, Kansas, Iowa, Nebraska, and South Dakota. Occasional beds of coal are present, probably formed about the borders of the sea, or about the islands which stood above it. Charred wood and even charcoal in



Fig. 506.— A group of concretions weathered out from the Dakota sandstone. Near Minneapolis, Kan. (Schaffner.)

the series point to the existence of fires during the epoch. The aggregate thickness of the series is locally as much as 3,000 feet, as strata are measured, though its average thickness is much less. The earlier formations of the Gulf region are probably not older than the Colorado series of the western interior.

The origin of the chalk.¹ There has been much difference of opinion concerning the origin of chalk. Its resemblance to the foraminiferal ooze of the deep seas long since led to the belief that it was a deep-sea deposit; but closer examination has thrown doubt on this conclusion, for the differences between the chalk and foraminiferal ooze are as striking as their likenesses. Both consist

¹ Wallace, *Island Life*. Also Chamberlin and Salisbury, Vol. III, p. 149.

largely of the shells of foraminifera; but with them are associated shells of other types, some of which are similar in the two formations, and some dissimilar. The echinoderms, the sponge spicules, and the secretions of certain microscopic plants correspond in a general way with those of the oozes now forming, and are consistent with the deep-water origin of the chalk. The molluscan shells of the chalk, on the other hand, seem to point with clearness to water no more than 30 to 50 fathoms deep. The distribution of the chalk and its relations to other sedimentary beds indicate its deposition in shallow water, not in water comparable in depth to that in which oozes are now formed. On the whole, the balance of evidence is in favor of the view that the Cretaceous chalk was deposited in relatively shallow water. The conditions for its origin seem to have been clear seas, with a genial climate. Its materials may accumulate as well on the bottom of a shallow sea as on the bottom of a deep one, if elastic sediments are absent.

The Montana series. Following the Colorado epoch, there were changes in the sedimentation and in the life of the western interior sea. The Montana series is chiefly elastic, but the area of sedimentation was somewhat contracted. The beds are, for the most part, marine, and the water shallowed as the epoch progressed. Local beds of coal give evidence of marshy conditions. Like other parts of the Cretaceous system of the west, the Montana series abounds in concretions, some of which attain great size. The thickness of the series is variable, and its maximum is great. From 8,700 feet in Colorado, it thins to 200 feet in some parts of the Black Hills. The Ripley formation of the Gulf region is of about the same age, probably, as the Montana series.

The Laramie.¹ Deposition continued in the Great Plains and to some extent west of them through the last epoch of the Cretaceous period, but most of the sedimentation was non-marine. Fresh-and brackish-water beds are widely distributed. The Laramie series may be said to record the transition from the marine conditions of the Montana epoch, to the fresh-water and land conditions of the

¹ For a full discussion of the Laramie (up to 1892) see White (C. A.), Bull. 82, U. S. Geol. Surv. A brief statement by the same author is found in the Proc. A. A. A. S., 1889, Vol. XXXVIII. See also folios of the Great Plains region, U. S. Geol. Surv.

Tertiary in the same region. This change probably did not take place everywhere at the same time, so that beds correlated with the Montana series at one point, are perhaps the time equivalents of beds classed as Laramie at other points. The series consists primarily of sandstone, and shale, with some conglomerate; but with these clastic formations there is much coal. Both shale and coal are more abundant below than above, while in the upper part of the series conglomerate is not rare. The materials of the Laramie formation seem to have been derived principally from the pre-Paleozoic rocks of the mountain region. The thickness of the Laramie is estimated at 1,000 to 5,000 feet, exclusive of the transition (Mesozoic-Cenozoic) beds to be mentioned below. In not a few places there is an unconformity in the great group of strata heretofore classed as Laramie, and there is difference of opinion as to whether the part above this unconformity should be called Laramie. The present tendency is to regard it as Eocene.¹ It may be added that there is difference of opinion as to whether there is one widespread, major unconformity at the horizon indicated above, or whether there are diverse local unconformities. If the former, it should have great weight in determining the classification. The latter would be less significant.

In a considerable area of northeastern Wyoming, and in a large area farther north,² some of the Laramie lignite has been burned in the ground. The burning was relatively recent, and locally is still in progress. The firing appears to have taken place at the outcrops on hill and valley slopes. The burning was accompanied by fusion, semi-fusion, and baking, resulting in lava-like slag and brick-red banks of indurated clay. The slag, etc., has had a notable effect on the details of the topography (Fig. 507) developed by wind and water, and the color effects of the burning are striking.

Coal. The Cretaceous is pre-eminently the coal period of the west. Coal-beds occur in every one of its principal divisions in

¹ The Laramie question is well reviewed by Cross, Washington Acad. of Sci., Vol. XI, pp. 27-45, 1909. Other recent discussions by Veatch are found in Am. Jour. Sci., Vol. XXIV, 1907, and Jour. Geol., Vol. XV, 1907.

² Allen, Proc. Boston Soc. Nat. Hist., Vol. XVI, p. 246, 1874; also Bastin, Jour. Geol., Vol. XIII, p. 408. These phenomena were noted and correctly interpreted by Lewis and Clark. See report of their expedition.

this part of the continent. The total amount of coal, chiefly in the Laramie, is perhaps comparable to that in the Pennsylvanian system, though the Laramie coal is not now so accessible, and its quality is inferior. It is estimated that along the east and west bases of the Rocky Mountains there are more than 100,000 square miles of coal-bearing lands, and Colorado alone is estimated to have 34,000,-



Fig. 507.—An outcropping ledge of clay, hardened by the burning of the coal-bed below. Except in the immediate vicinity of the burnt-out coal-bed, the clay is not indurated. Near Buffalo, Wyo. (Blackwelder.)

000,000 tons of available coal,¹ most of which is Cretaceous. The coal is largely lignite, though in Colorado not a little of it has been advanced to coking bituminous coal, and even to anthracite.² Anthracite referred to the Laramie also occurs farther south in localities where it has been affected by intrusions of igneous rock. The areas of Laramie coal are indicated in Fig. 438.

Transition beds between Mesozoic and Cenozoic. There are diverse, more or less local, terrestrial formations in the west which have been referred now to the Cretaceous (Laramie,—or more

¹ Storrs, 22d Ann. Rept., U. S. Geol. Surv., Pt. III.

² Anthracite—Crested Butte folio, U. S. Geol. Surv.

exactly, to the upper Laramie or post-Laramie), and now to the Tertiary (Eocene). They have heretofore been regarded, most commonly, as the transition beds between the Cretaceous and the Tertiary. It has been proposed recently to group these formations together under the name *Shoshone*, and to class them as Eocene.¹ These formations are, generally speaking, unconformable on the Laramie and, in some places seem hardly separable from the recognized Tertiary² (Fort Union). Their reference to the Eocene seems to be justified both on stratigraphic and paleontologic grounds, so far as present data are concerned.

*The Pacific Coast*³

The Cretaceous system is represented on the Pacific coast by the marine *Chico* series. At the time of its origin, this series probably extended along the coast from Lower California to the Yukon. The *Chico* series rests on the Shastan unconformably in some places,⁴ and overlaps it at others.⁵ The fauna of the *Chico* series is littoral. Its oldest portion is older than the fauna of the Colorado series, and its youngest is older than the fauna of the youngest Cretaceous beds in some other places.⁶

Close of the Period

About the close of the Cretaceous period a series of disturbances was inaugurated on a scale which had not been equalled since the close of the Paleozoic era. These changes furnish the basis for the classification which makes the close of this period the close of an era. These disturbances continued into later times, but the close of the Cretaceous may be said to have been the time when the changes had advanced so far as to make themselves felt profoundly. They consisted of deformative movements, a part of which were orogenic, and of igneous eruptions on an almost unprecedented scale.

¹ Cross, see footnote, p. 750.

² Here belong the Arapahoe, Denver, Middle Park, and Animas beds of Colorado, the Carbon, Evanston, and Ceratops beds of Wyoming, and the Hell Creek, and perhaps the Livingston beds (at least in part) of Montana.

³ Papers of Diller, Stanton, and Turner, cited under the Lower Cretaceous (Shasta), p. 733.

⁴ Fairbanks, Jour. Geol., Vol. III, p. 426.

⁵ Fairbanks, Am. Jour. of Sci., Vol. XLV, 1893, p. 478.

⁶ Stanton, Jour. Geol., Vol. XVII.

General movements. In the closing stages of the period, the sea which had lapped over the Coastal Plains of the Atlantic and the Gulf of Mexico was withdrawn toward the abysmal basin. At about the same time, the Appalachian Mountains, which had been reduced to a peneplain by this time, were bowed up again. This later movement was chiefly vertical, while the Permian deformation was primarily horizontal,— a folding movement.

In the western interior, the sea had abandoned the area of the Great Plains, and other tracts in the mountains farther west, before the close of the Laramie. It is probable that most of the Cordilleran region was elevated bodily at this time, though not to



Fig. 508.—Section showing the position of the Cretaceous beds in western Oregon. *Mg*, meta-gabbro of unknown age; *sp*, serpentine; *as*, amphibolite schist; *Jr*, Jurassic (?); *Km* (Myrtle formation), Cretaceous, and *Kmw*, lentils of limestone in the Myrtle formation; *Eu* (Umpqua formation), Eocene; *Ed*, Eocene diabase. (Diller, Roseburg, Ore., folio, U. S. Geo. Surv.)

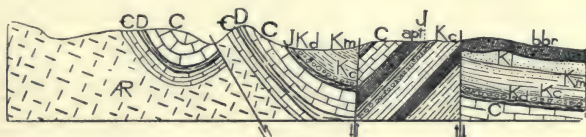


Fig. 509.—Section showing position of Cretaceous beds at one point in the vicinity of Livingston, Montana. *A* = Archean; *C*, Cambrian (Gallatin and Flathead formations); *D*, Devonian (Jefferson formation); *C*, Carboniferous (Quadrant and Madison formations); *J*, Jurassic (Ellis formation); *Kd*, Dakota formation; *Kc*, Colorado series; *Km*, Montana series, and *Kl*, Laramie series; *bbr*, basic igneous rock, and *apt*, acidic rock. Length of section about 11 miles. (Livingston, Mont., folio, U. S. Geol. Surv.)

a great height. Without further details, it may be said that enough is known to make it probable that a large part of the continent was affected by deformative movements of a gentle sort.

Orogenic movements. The growth of mountains locally by folding was probably in progress in the closing stages of the Cretaceous period from Alaska on the north to Cape Horn on the south,—more than a quarter of the circumference of the earth. Folding

movements probably affected the Antillean mountain system,¹ between the southern end of the Cordilleran and the northern end of the Andean systems, at the same time, for in several of the Antillean islands later formations rest unconformably on the deformed Cretaceous beds. Where the Eocene rests conformably on the Laramie, the disturbances of this time are not clearly distinguishable from those of later date, which increased the folding initiated

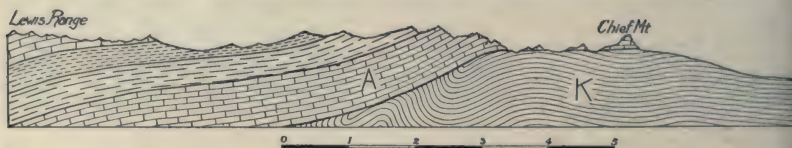


Fig. 510.—Section in northern Montana, showing Proterozoic rock, *A*, thrust over Cretaceous, *K*. Subsequent erosion has removed much of the overthrust beds, but Chief Mountain is a remnant of them. The extent of the overthrust is unknown.



Fig. 511.—Chief Mountain. (Willis, U. S. Geol. Surv.)

in this epoch. Some of the folded ranges of the western mountains began their history at this time, others had a new period of growth, and still others date from a later time; yet the close of the Laramie was a time of general orogenic movement in the western part of

¹ Hill, Nat. Geog. Mag., Vol. VII, p. 175.

North America. The Rocky Mountain system may be said to have had its birth at this time. That these mountains are not older is shown by the deformation of the Laramie beds along with those of greater age. That some of the folding was not younger, is shown by the lesser deformation of the Tertiary beds in the same region. It should be added that most of the western mountains which began their history at this time are unlike the Appalachians, as developed at the close of the Paleozoic. In the first development of the latter, horizontal movement was the great factor involved; in most of the former, vertical movement.

Faulting. The growth of mountains at the close of the Cretaceous was accompanied by faulting on a somewhat extensive scale throughout the region of movement, though the faulting of this time cannot always be distinguished from that of later date. In the Rocky Mountains of British Columbia, one overthrust fault has been located which crowded the Cambrian rocks obliquely up over the Cretaceous. The horizontal displacement is estimated to be as much as seven miles,¹ and the throw 15,000 feet. Near the national boundary, the displacement of what appears to be the same fault crowded the Proterozoic up over the Cretaceous² by a movement of equal magnitude (Fig. 510). The exact date of these faults has not been determined, but was, perhaps, mid-Tertiary.

Igneous eruptions. The close of the Cretaceous was marked by the inauguration of a period of exceptional igneous activity, continuing far into the Tertiary. During this period, great bodies of igneous rock, both extrusive and intrusive, were forced up. Eruptions occurred in other lands at about the same time.

UPPER CRETACEOUS OF OTHER CONTINENTS³

Europe. The distribution of the Upper Cretaceous strata of Europe shows that extensive transgressions of the sea occurred at the beginning of the period, for in some parts of the continent, marine Cretaceous formations overlap all older Mesozoic systems.

¹ McConnell, Geol. Surv. of Canada, Vol. II, Rept. D, p. 33, 1886.

² Willis, Bull. Geol. Soc. of Am., Vol. XIII, pp. 307, 331-335.

³ The term Comanchean has not been applied outside of North America, and the Cretaceous system will therefore be referred to as Upper Cretaceous.

During the closing stages of the Upper Cretaceous, fresh-water beds appear in localities (alpine region) where marine sedimentation had been in progress earlier in the period, showing that the movements

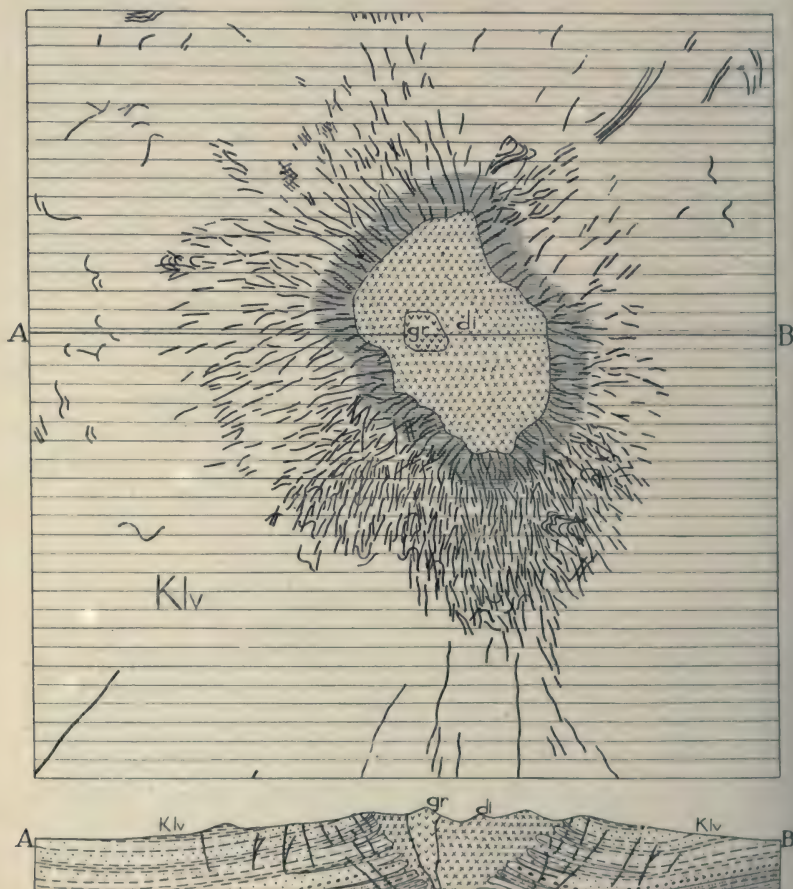


Fig. 512.— Map and section showing relations of igneous rock to the Cretaceous formations in the Crazy Mountains of Montana. The section is along the line *AB* of the map. *Klv*, Livingston formation; *di*, diorite; *gr*, granite. The especial feature of the map is the extraordinary number of dikes radiating from the central intrusion, *di*. The shaded area about *di* represents the zone of contact metamorphism about the intrusion. Length of section about 20 miles. (Livingston and Little Belt, Mont., folios, U. S. Geol. Surv.)

which were to mark the close of the era were making themselves felt.

Limestone is the dominant sort of rock in the Upper Crustaceous of southern Europe, showing that clear seas still prevailed, as in the Early Cretaceous period. From a characteristic genus of fossils, much of the limestone is known as *Hippurite* limestone. In the system farther north, there is more clastic material.

The most notable petrographic feature of the Upper Cretaceous of Europe is the chalk. Both in England and France it attains an aggregate thickness of several hundred feet, though much of it is far from pure. It grades into marls and clays on the one hand, and into sandstone on the other. Chalk is, however, by no means coextensive with the system, for it has little development outside of the Anglo-French area. The name "Cretaceous," therefore, *as generally used*, is as inappropriate as a name could well be, having no applicability to the Lower Cretaceous, and fitting only a relatively small area of the Upper. Even within the areas where chalk occurs, it is not everywhere the dominant sort of rock. Greensand occurs in the Upper Cretaceous as well as in the Lower. The principal subdivisions of the system recognized in western Europe are 1. Albian; 2. Cenomanian; 3. Turonian; 4. Senonian, and 5. Danian, numbered from the base up.

Asia. The submergence of Europe and North America at the beginning of the Upper Cretaceous finds its parallel in other continents. There are extensive areas of *Hippurite* limestone in southwestern Asia, closely connected with that of Europe on the one hand, and with that of North Africa on the other. The Himalayan region seems to have been still beneath the sea, for Upper Cretaceous formations are found in the mountains at great elevations. Greensand occurs in the Salt Range of India.¹ South of these marine beds there appears to have been a large tract of land, including much of the peninsula of India, which has been thought to have stretched southwest to Africa, though the configuration of the sea-bottom does not lend this view much support.

Upper Cretaceous beds occur on the eastern coast of China, and in Japan. In many places they rest on formations older than the Lower Cretaceous, and therefore record an increased submergence

¹ Seeley, *Geol. Mag.*, 1902, p. 471.

dating from the beginning or early part of the Upper Cretaceous. On the other hand, northern Asia, which was largely submerged during the earlier Cretaceous period, was largely land during the later.

Late in the Upper Cretaceous occurred the extensive lava-flows of the Deccan. These flows, 4,000 to 6,000 feet in thickness, cover an area of something like 200,000 square miles, and are perhaps the most stupenduous outflows of lava recorded in the earth's history. The fossils in sediments interbedded with the lava show that the flows were subaërial.

Africa. In northern Africa, the Lower Cretaceous beds are confined to the northwestern mountains, but the Upper Cretaceous beds, which overlie the Lower unconformably,¹ spread southward and cover most of the desert, indicating great submergence in the north African region. South of the Sahara, no Upper Cretaceous beds are known except in a few small areas about the coast, where they rest on crystalline schists with no Lower Cretaceous beds beneath, so far as now known.

South America. In South America, the sea invaded eastern Brazil, where marine Upper Cretaceous beds cover and overlap the non-marine Lower Cretaceous. In some parts of Brazil, however, the Upper Cretaceous is represented by fresh-water beds only. Farther west, marine Upper Cretaceous beds rest unconformably on the Lower Cretaceous, and form the summits of much of the eastern Andes, occurring up to altitudes of 14,000 feet at many points, and locally even higher. Upper Cretaceous beds also occur in southern Patagonia. There appears to have been great volcanic activity in the Andean system (Chile and Peru) during the late Cretaceous.

Australia. The phenomena of Australia are in harmony with those of the other continents. The Upper Cretaceous beds are wide-spread, locally resting on formations older than the Lower Cretaceous. Furthermore, the Upper Cretaceous (*Desert Sandstone*) is in many places unconformable on the upturned and denuded Lower Cretaceous, showing that there were deformative movements, as well as movements which changed the relations of

¹ Kayser, *Geologische Formationskunde*, p. 443.

sea and land, after the deposition of the Lower Cretaceous beds and before the deposition of the Upper.

General. In general it may be said that there was little marine sedimentation in the Late Cretaceous period north of the parallel 60° north, while the Jurassic and Lower Cretaceous systems are there more wide-spread. Between the parallels of 20° and 60°, on the other hand, the zone where marine Lower Cretaceous is but slightly developed, the Upper Cretaceous system is wide-spread. Outside of China, the Upper Cretaceous system is wanting over no considerable land-area within these limits. In the equatorial and south temperate zones, the Upper Cretaceous seas were also expanded much beyond the limits of the waters of the preceding period.

Climate

The climate of North America throughout most of the Cretaceous period seems to have been rather uniform and warm throughout a great range of latitude. In Greenland, Alaska, and Spitzbergen, the climatic conditions seem to have been similar to those in Virginia. Toward the close of the period the temperature was perhaps lower, for the Laramie flora is a temperate, rather than a tropical one. The fresh-water fossils of central Europe indicate a climate comparable to that of Malaysia.¹ As this seems to have been a period of low land, widely extended epicontinental seas, extensive calcareous deposits, and slow consumption of carbon dioxide in rock solution and carbonation, there was a combination of conditions regarded as favorable for a mild and uniform climate.

LIFE OF THE (UPPER) CRETACEOUS

The Land Plants

Angiosperms predominated in North America at the beginning of the Cretaceous, and during the period genera now living came to be numerous, giving the flora a modern aspect. Among the living genera of angiosperms (Fig. 513) that made their appearance were those which include the birch, beech, oak, walnut, sycamore, tulip-tree, laurel, cinnamon, maple, holly, sweet-gum, ivy, and

¹ Neumayr, *Erdegeschichte*, Bd. II, p. 383.



Fig. 513.—A GROUP OF FOSSIL LEAVES OF TYPICAL CRETACEOUS PLANTS FROM THE DAKOTA HORIZON. a, *Liriodendron giganteum* Lesq.; b, *Myrica longa* Heer; c, *Magnolia pseudoacuminata* Lesq.; d, *Sterculia mucronata* Lesq.; e, *Quercus suspecta* Lesq.; f, *Viburnum inaequilaterale* Lesq.; g, *Betulites westi*, var. *subintegrifolius* Lesq.; h, *Sassafras subintegrifolium* Lesq.; i, *Ficus inaequalis* Lesq.

oleander. Among the gymnosperms, there was a notable development of the sequoias, which now include the giant trees of California. The modern *Cycas* was present, and the ginkgo had some prominence, though never a leading type. Worthy of special note was the presence of genera in Europe and the United States which are now confined to the southern hemisphere, as *Podocarpus*, the leading pine of the southern hemisphere. Some of these remained in the northern regions till the early Cenozoic.

Previous to the later stages of this period, monocotyledons played but an insignificant part in the floral record, but they now began to assume a position of importance. *Palms* were plentiful, even in northerly latitudes, before the close of the period, and some of them were closely allied to existing palms. Of even more interest, because of their relations to the evolution of grazing animals, was the appearance of *grasses*, which do not, however, appear to have attained prominence until later.

It is worthy of remark that the introduction of dicotyledons, the great bearers of fruits and nuts, and of monocotyledons, the greatest grain and fodder producers, was the groundwork for a profound evolution of herbivorous and frugiverous land animals, and these in turn, for the development of the animals that prey upon them. A zoölogical revolution, as extraordinary as the botanical one, might naturally be anticipated; but it did not follow immediately, so far as the record shows. The reptiles seem to have roamed through the new forests as they had through the old, without radical modification. The zoölogical transformation may have been delayed because the appropriate animals had not then come into contact with the new phases of plant life. With the opening Tertiary, the anticipated revolution in the animal life of the land made its appearance, and advanced with great rapidity.

The new flora spread widely. Not only was the European flora essentially the same as the American, but there was a close resemblance between the flora of mid-Greenland (70°–72° Lat.) and that of Maryland and Virginia, indicating climatic conditions of remarkable uniformity. Not only this, but the flora was of a sub-tropical type.

The Land Animals

The terrestrial animals had the same general aspect as in the preceding period. In Europe, where the sea made great inroads upon the land, there was some decline in their abundance, variety and proportions; but in America, the area of land was not small enough to restrain greatly the evolution of the reptiles. On both continents the aquatic reptiles seem to have made greater progress than the terrestrial forms.

The *dinosaurs* still retained the leading place among the land reptiles, though the carnivorous forms (*Theropoda*) were less abundant and varied than before. Among them was a leaping, kangaroo-like form (*Laelaps* or *Dryptosaurus*) with a length of 15 feet. The most singular dinosaurian development was among the herbivorous branch, some of which were very large, of quadrupedal habit, with enormous skulls which extended backwards over the neck and shoulders in a cape-like flange (Fig. 514). Added to this was a sharp, parrot-like beak, a stout horn on the nose, a pair of large pointed horns on the top of the head, and a row of projections around the edge of the cape. One of the larger skulls measures eight feet from the snout to edge of the cape. This excessive provision for defense was not unnaturally accompanied by evidences of low mentality, in the form of a very small brain cavity. Marsh remarks that they had the largest heads and the smallest brains of the reptile race. They were doubtless stupid and sluggish. The ornithopod division was well represented (Fig. 516). Their posterior parts were strongly developed, their limbs were hollow, and their footprints indicate that they walked in kangaroo-like attitude. Save for the thalattosaurs, some of the dinosaurs (of the *Niobrara*) were among the first distinctively American air-breathing forms since the Permian.

Distinctively terrestrial *turtle* remains are found in the Dakota sandstone, and the fossils of species inhabiting fresh waters have been found in the late Cretaceous (Belly River) deposits of Canada. Of true *lizards*, which appeared in the Triassic, only one later Mesozoic form is known, and that of small size and uncertain affinities from the Laramie. *Snakes* made their first appearance, so far as



Fig. 514.— *Triceratops prorsus* Marsh, from the Laramie Cretaceous. (From a painting by C. R. Knight in the U. S. National Museum.)



Fig. 515.— Spoonbill Dinosaurs of the Cretaceous (*Hadrosaurus mirabilis* Leidy) as interpreted by Knight. (Osborn, Copyrighted by the Am. Mus. of Nat. Hist.)

known, in the later part of the period, but they were small. Among the *crocodiles*, the long-snouted teleosaurs persisted, in North America at least, until well into the Cretaceous; but for the most part the order underwent a marked change early in the period, developing into the modern type of crocodiles and gavials. A few



Fig. 516.— A Cretaceous dinosaur of the ornithopod division, *Claosaurus annectens*. (Restored by Marsh.)

small *salamanders*, of modern type, are known from the late Cretaceous.

The *flying reptiles* made so distinct an advance in specialization, that Williston regards them as having come to excel all other flying vertebrate animals. Some attained a wing-spread of perhaps 20 feet. In some of the genera (Fig. 517) the development of the anterior parts was disproportionately great, while the posterior parts were so very small and weak that it is doubtful whether they could stand on their feet alone. The Cretaceous forms were all short-tailed, and for the most part toothless, though the toothed

forms persisted for a while. Their bills resembled those of modern birds.

Terrestrial *birds* existed, but the fossil record of them is meager. There were some curious aquatic forms, which will be mentioned in connection with the sea-life. The *mammals* thus far recovered from the Cretaceous indicate little advance upon those of the

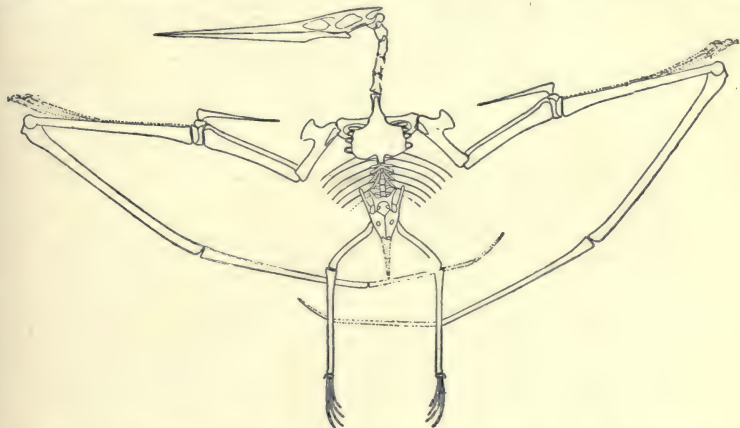


Fig. 517.— A Cretaceous pterodactyl, *Nyctosaurus gracilis* Marsh, about $\frac{1}{10}$ natural size, from Niobrara Cretaceous, Kansas. (Restored by Williston.)

Jurassic. Mammals appear to have played a very inconspicuous part in the fauna of the period.

The Sea Life

Vertebrates. The *ichthyosaurs* and *plesiosaurs* which had dominated the Jurassic sea lived on into the Cretaceous. The former dropped into an insignificant place soon after the beginning of the period, but the plesiosaurs attained their highest development and perhaps their greatest size, during the period. The American types of plesiosaurs indicate lack of intermigration between this continent and Europe.

The aquatic branch of the scaled saurians (*Squamata*) attained great importance as veritable sea serpents. The long-necked, lizard-like reptiles of the Comanchean period were the forerunners

and perhaps the direct ancestors, of the *mosasauroians* (Fig. 518), a family which flourished in the Cretaceous, and ranged from North and South America to Europe and New Zealand. Their short career seems to have ended with the period, and no direct descendants are known.



Fig. 518.— A Cretaceous mosasaurid, *Platacarpus coryphaeus* Cope, restored by Williston; from Upper Cretaceous, Kansas.

Marine *turtles* seem to have appeared first in this period, and to have developed into many and diverse forms. The largest were broad, and flat, degenerate in having the carapace reduced to the ribs alone, and probably covered with a soft skin, like some living marine turtles. Some of them had skulls larger than those of horses and must have measured fully twelve feet across the shell.



Fig. 519.— *Champsosaurus*, from the Laramie of Montana. Length, about six feet. (After Brown.)

In the long interval between the first known appearance of *birds* in the Jurassic, and the later Cretaceous when they reappeared, important changes took place, among which was the loss of the elongate, bilaterally feathered tail. The Jurassic birds were terrestrial, while the Cretaceous were aquatic. The Cretaceous birds include about 30 species belonging to two widely divergent orders, *Hesperornis* and *Ichthyornis*. The former (Fig. 520) were large,

flightless, highly specialized divers, with aborted wings and remarkable legs. This implies that, following the evolution which had produced the wings, there had been a degenerative history long enough for them to dwindle almost to the point of extinction. Concurrent with this, and doubtless its cause, was an extraordinary development of the legs. They were not only very powerful, but the bones of the feet were so joined to the legs as to allow the feet



Fig. 520.— Restoration of the great toothed diver of the Cretaceous, *Hesperornis*, by Gleeson, based on a skeleton in the U. S. National Museum. (From Lucas' *Animals of the Past*; by permission of the Publishers, McClure, Phillips & Co.)

to turn edgewise in the water when brought forward, thus increasing their efficiency as paddles. Furthermore, the legs were so joined to the body frame as to stand out nearly at right angles to it, like a pair of oars, instead of standing under the body like walking legs.¹ Apparently, walking as well as flying had been abandoned, and the organism was specialized for swimming and diving only. For this purpose, the head, neck, and body were admirably adapted. The jaws were armed with teeth set in a groove in primitive saurian fashion, and, like the jaws of snakes, were separable so as to admit

¹ Lucas, *Animals of the Past*, 1901, pp. 81–85.

large prey. As these strange birds attained a length of six feet in some cases, they were doubtless formidable enemies to the sea life on which they choose to feed, and their victims may have embraced fish and reptiles of considerable size. As they have been found in Kansas, Montana, North Dakota, New Jersey, and England, they probably frequented the epicontinental seas somewhat widely, and belong more to the sea life than to the land life from which they sprang.

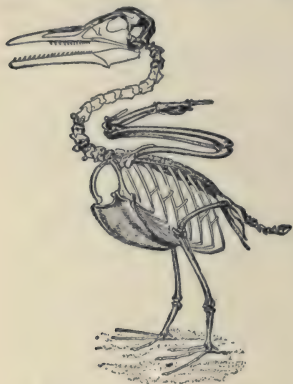


Fig. 521.—*Ichthyornis victor*, a Cretaceous toothed bird of flight, $\frac{1}{10}$ natural size. (Restored by Marsh.)

The second type, *Ichthyornis* (Fig. 521), was scarcely larger than a pigeon, endowed with great power of flight, as indicated by the strong development of the wings and keel. At the same time, their legs and feet were small and slender. They had teeth set in sockets. Their biconcave vertebræ and other skeletal features, as well as their small brains, suggest reptilian relationships. Their habitat was the same as that of *Hesperornis*, and yet the two were farther apart, structurally, than any two types of birds now living (Marsh).

An important change took place in the *fish* of the sea, in the transfer of dominance from the older types to the *teleosts*. This change set in during the Comanchean, and was complete by the middle of the Cretaceous. Though modern in type, the species were in the main ancestral, and some of them are not yet extinct. The sharks and rays were chiefly of the modern types, though not of living species.

Invertebrates. The most notable departure from the precedents of the preceding ages is the prominent place which the *rhizopods* or *foraminifers* take in the record. They made large con-

Fig. 522.—CRETACEOUS FOSSILS. *a-e*, Echinoderms: *a*, *Pedinopsis pandi* Clark; *b*, *Cassidulus subquadratus* Con.; *c*, *Botreopygus alabamensis* Clark; *d* and *e*, *Salenia tumidula* Clark. *f*, *g*, and *h*, Pelecypods: *f*, *Ostrea soleniscus* Meek; *g*, *Idoneurca nebrascensis* Owen, allied to the areas of to-day; *h*, *Inoceramus vanuxemi* M. and H. *i-l*, Gastropods: *i*, *Neptunella intertextus* (M. and H.); *j*, *Aphorrhais prolabiata* (White); *k*, *Drepanochilus nebrascensis* (E. and S.); *l*, *Pyropsis bairdi* (M. and H.)



Fig. 522.— (For description, see opposite page.)

tributions to the chalk of the period, and they were concerned in the formation of the greensand, scarcely less characteristic of the period than the chalk. While some of these minute organisms live on shallow bottoms, on fixed algæ, and in abysmal water, they are chiefly inhabitants of the surface waters of the open sea.

Sea-urchins were quite abundant, and lent one of its character-



Fig. 523.—Cretaceous Cephalopods: *a*, *Nautilus meekanus* Whitf., one of the simplest types of closely coiled cephalopods; *b*, *Helicoceras stephensoni* Whitf., an ammonite coiled in a heliciform spiral, and *c*, its highly complicated suture; *d*, *Prionotropis woolgari* (Mantell), a normal ammonite with ornamented shell and *e*, complex sutures; *f*, *Ptychoceras crassum* Whitf., an ammonite shell which is recurved upon itself, but not coiled; *g*, suture of *f*; *h*, *Scaphites nodosus* Owen, an ammonite showing a slight tendency to uncoil in the last volution; *i*, *Baculites grandis* M. and H.

istic aspects to the fauna, while *corals* and *crinoids*, so long associated with clear seas, were not abundant.

In the clastic formations, *pelecypods* and *gastropods* are abundant and characteristic fossils (Fig. 522). It will be seen by a glance at the figures that they have a modern appearance. *Cephalopods* were still abundant, though ammonites were in their decline and were showing erratic divergencies of form, attended by excessive ornamentation, comparable to that which marked corresponding stages of the trilobites and crinoids. Odd forms of partial uncoiling, or of spiral and other unusual forms of coiling, were common (Fig. 523). Interesting forms, perhaps to be classed here, were the *Baculites* (*i*), which resumed the straight form of the primitive *Orthoceras*, while retaining the very complicated sutures of the *Ammonites* (*c*).

Map work. Folios of the U. S. Geological Survey containing good maps for the study of the Comanchean and Cretaceous systems are the following: *Arizona*, Bisbee, Clifton, Globe; *California*, Colfax, Lassens Peak, Mother Lode, Redding, Sacramento, San Luis; *Colorado*, Anthracite and Crested Butte, Elmore, La Plata, Nepesta, Pueblo, Spanish Peaks, Telluride, Walsenburg; *District of Columbia*, Washington; *Delaware-Maryland-New Jersey*, Dover; *Oklahoma*, Atoka, Tishomingo; *Montana*, Fort Benton, Little Belt, Livingston, Three Forks; *New York*, New York City (Staten Island and Harlem sheets); *Oregon*, Roseburg, Coos Bay, Port Orford; *South Dakota*, Edgemont, Oelrichs; *Texas*, Austin, Nueces, Uvalde; *Virginia*, Fredericksburg; *Wyoming*, Alladin, Cloud Peak-Fort McKinney, Devils Tower, Hartville, Newcastle, Sundance, Yellowstone.

Both Comanchean and Cretaceous are classed as Cretaceous in the folios, though often distinguished in the text and on the maps.

THE CENOZOIC ERA

CHAPTER XXVII

THE EOCENE PERIOD

FORMATIONS AND PHYSICAL HISTORY

The remaining periods of geological history constitute the Cenozoic era, or the era of modern life. The era is variously subdivided, as shown below:

Cenozoic Era	Quaternary	Recent or Human. Post-glacial formations		
		Pleistocene or Glacial. Glacial formations and non-glacial deposits of glacial age		
	Tertiary	Pliocene	Pliocene	Neocene
		Miocene	Miocene	
		Oligocene	Eocene	Eocene
		Eocene		

The threefold subdivision of the Tertiary (Eocene, Miocene, Pliocene) is the one which seems to fit the phenomena of our continent best, but there is a growing tendency toward the recognition of the Oligocene. This means that beds are found in our continent with fossils similar to those of the Oligocene of Europe, rather than that the Oligocene of this continent constitutes a natural and major subdivision of the Tertiary.

Eocene formations are found in widely separated parts of North America (Fig. 524), though they do not appear at the surface over large areas. They include beds laid down in the seas and bays, and on the land. The former include formations of marine and brackish-water origin, and the latter those of lacustrine and subaërial (fluvial, pluvial, eolian) origin. The subaërial formations are probably more important than has commonly been recognized. The marine and brackish-water beds are confined to the borders of the continent, while the terrestrial deposits are found in many places in the Great Plains and farther west. Many of the formations are not indurated, but locally they are even metamorphosed.



Fig. 524.—Map showing the distribution of the Eocene formations in North America. The conventions are the same as in former maps.

The eastern coast. Eocene formations appear at the surface in an interrupted belt from New Jersey to Texas. Their structure is similar (Fig. 499) to that of the Cretaceous, from which they are separated by an unconformity. The materials of the Eocene were derived largely from the Cretaceous, and subordinately from older formations farther inland. Clays, sands, and greensand marls are the most common materials of the system, and the conditions of sedimentation were much as in the preceding period.

The system is more fully represented in the Gulf region than on the Atlantic coast, and is thicker (1,700 feet maximum). It contains much lignitic matter in places, showing that marine conditions were not uninterrupted. In Texas,¹ gypsiferous and saliferous sediments recur at various horizons, though most of the beds are of marine origin, and there are numerous local unconformities in the system, suggesting recurrent changes in the conditions and areas of sedimentation. The principal subdivisions² are (1) Midwayan; (2) Chickasawan; (3) Claibornian, and (4) Jacksonian.

The Pacific coast. Marine and brackish-water beds.³ Marine Eocene formations are wide-spread west of the Sierra and Cascade ranges of California, Oregon, and Washington (Fig. 525), and have considerable development in Alaska. Throughout Washington and Oregon and in some parts of California, the Eocene is unconformable on the Cretaceous (in most places on the Lower Cretaceous = Comanchean or Shastan), while in much of California it is conformable on the Chico, the division plane between the two being indicated by a paleontological hiatus. These relations suggest that just before the Eocene, all of Washington, most of Oregon, and parts of the coastal region of California were land, over which the sea advanced later. The Coastal lands of the time were mostly low, but in southern Oregon and northern California there seem to have been mountainous areas, as also at some points farther south.

¹ Dumble, Jour. Geol., Vol. II; also Reports of the Texas Geological Survey, and the Austin and Uvalde folios, U. S. Geol. Surv.

² Dall, 18th Ann. Rept., U. S. Geol. Surv., Pt. II. This classification places the Vicksburg in the Oligocene, instead of associating it with the Jacksonian. There appears to be no *physical* reason for this separation.

³ Arnold, Jour. Geol., Vol. XVII.

The rocks of the Eocene system are mostly clastic, sandstone and shale predominating, but there are conglomerates, tuffs, and diatomaceous shales, the last thought to be a source of oil. In not a few places, marine beds are succeeded by brackish-water deposits.

By the beginning of the Eocene, the Puget Sound depression, perhaps to be correlated with the great valley of California and the Gulf of California, had begun to show itself.¹ The Olympic and Cascade mountain regions on either side were high lands, but not mountainous; and the region of the sound was a great estuary, in and about which deposition was in progress. Some of the sediments accumulated in brackish water and on land, and resulted in the thick coal-bearing Puget series of Washington, the upper part of which is Oligocene or even Miocene.² The series is said to contain 125 beds of coal thick enough to attract prospectors. Most of the workable coal is in the lower part of the series. The area of deposition extended south into Oregon, and east well toward the Blue Mountains of that state.

British Columbia appears to have been land during the period,³ but Eocene beds, much disturbed,



Fig. 525.—Map showing supposed distribution of land and water on the Pacific coast of the United States during the Eocene period. (Ralph Arnold.)

¹ Willis, Tacoma folio, U. S. Geol. Surv.

² Willis, Bull. Geol. Soc. Am., Vol. IX, 1897-8. See also 18th Ann. Rept., U. S. Geol. Surv., and Landes, Washington Geol. Surv., Vol. II, p. 170.

³ Dawson, Science, Vol. XIII, 1901, p. 401. Also Spencer, A. C., Bull. Geol. Soc. Am., Vol. XIV, p. 131.

have been recognized in Alaska (*Kenai series*) where they are coal-bearing in places.

The Eocene system has an estimated thickness of 10,000 to 12,000 feet in southern Oregon, and but little less in southern California.

After the Eocene, there was a time of temporary elevation, erosion, and volcanic activity along the Pacific coast, with considerable basaltic flows in Washington and Oregon.

The western interior. The warpings, faultings, and the intrusions and extrusions of lava which marked the close of the Mesozoic era in the west appear to have developed lands which were relatively high, adjacent to tracts which were relatively low. The steep slopes of the mountain folds, fault scarps, and volcanic piles seem to have afforded the conditions for rapid erosion, while the adjacent lowlands furnished places of lodgment for much of the sediment. Some of it took the form of fans and alluvial plains, and some of it probably lodged in lake basins formed by warping, or by the obstruction of valleys by lava flows. The wind also made its contribution to the deposits of the time. The result was an inextricable combination of fluvial, pluvial, eolian, and lacustrine deposits. Deposition on land was therefore a feature of the period, as of all subsequent time, and among the accessible formations of this and later periods, those of terrestrial origin are more widespread than those of marine origin.

The sites of principal sedimentation shifted somewhat from time to time, and among the widely distributed deposits referred to this period, there are great differences of age. Several more or less distinct stages of deposition have been made out, the distinctions being based partly on the superposition of the beds, and partly on their fossils.¹ These several stages are not readily correlated with those of the coasts.

1. Reference has already been made to certain formations which have been classed commonly as Cretaceous, which should probably be regarded as early Eocene (p. 752). Some of these

¹ For an account of the deposits near the 40th parallel, see King's report, Vol. I, already cited. For an attempt at correlating the several formations, see Dall, 18th Ann. Rept., U. S. Geol. Surv., Pt. II; also J. H. Smith, Jour. Geol., Vol. VIII, pp. 444-471.

TABLE OF TENTATIVE CORRELATIONS OF THE TERTIARY FORMATIONS OF CALIFORNIA, OREGON, AND WASHINGTON.

TABLE OF TENTATIVE CORRELATIONS OF THE TERTIARY FORMATIONS OF CALIFORNIA, OREGON, AND WASHINGTON.

Geologic Era	Quaternary		Tertiary		Cenozoic		Paleozoic		Pre-Cambrian					
	Recent	Alluvium	Central Washington	Western Washington	Eastern Oregon	Western Oregon	Mount Diablo Region	Santa Cruz Mountains	San Luis Potosi	Santa Maria District	Coahuila District	Veracruz County	Los Angeles County	San Diego Region
Quaternary		Alluvium		Alluvium	Alluvium	Alluvium	Alluvium	Alluvium	Alluvium	Alluvium	Alluvium	Alluvium	Alluvium	Alluvium
		San Pedro		Vaahoon		Marine Sands	Marine Sands	Marine Sands	Marine Sands	Marine Sands	Stream Deposits		San Pedro	San Pedro
		Unconformity		Admiralty		Unconformity	Unconformity	Unconformity	Unconformity	Unconformity			Unconformity	Unconformity
		Morced			Rattlesnake		Siesta	{ Merced Santa Clara	Paso Robles	Paso Robles			Beds at Deadman	Beds at Third Street Tunnel and Fender and Canyon
Tertiary		San Diego					Orindan	Purissima	Unconformity	Fernando	Unconformity	Fernando		Fernando
		San Pablo				Empire	San Pablo	S. Margarita	{ Plumas S. Margarita	Unconformity	Richards		Unconformity	Beds at Carrizo Creek
		Unconformity					County	Unconformity	Unconformity	Unconformity	Richards		Unconformity	
		Monterey				Astoria	Monterey	Monterey	Monterey	Monterey	Unconformity	Modelo		Unconformity
Cenozoic		Unconformity				Astoria	Unconformity	Unconformity	Unconformity	Unconformity	Unconformity	Vaqueros	Puebla	
		Unconformity				Astoria	Unconformity	Unconformity	Unconformity	Unconformity	Unconformity	Vaqueros		
		Unconformity				Astoria	Unconformity	Unconformity	Unconformity	Unconformity	Unconformity	Vaqueros		
		San Lorenzo				Astoria	Unconformity	Unconformity	Unconformity	Unconformity	Unconformity	Vaqueros		
Paleozoic		Tejon				Coaledo	Tejon			Tejon				
		Tejon				Coaledo	Tejon			Tejon				
		Tejon				Coaledo	Tejon			Tejon				
		Tejon				Coaledo	Tejon			Tejon				
Pre-Cambrian		Marina				Pulaski	Marines			Tejon		Topatopa		Chico
		Marina				Pulaski	Marines			Tejon		Topatopa		Chico
		Marina				Pulaski	Marines			Tejon		Topatopa		Chico
		Marina				Pulaski	Marines			Tejon		Topatopa		Chico

beds are inseparable from the *Ft. Union formation* (or series), heretofore regarded as the oldest division of the Tertiary in the western interior. During the *Ft. Union* stage, there was an extensive area of aggradation in parts of North Dakota¹ and Montana, and a still larger area in Canada. The *Fort Union* beds, composed of sand, clay, etc., are said to be locally 2,000 feet or more thick, and have usually been described as lacustrine. The presence of freshwater shells (unios, etc.), is consistent with this conclusion for some parts of the formation; but the abundance of the leaves at many places is indicative of subaërial aggradation for other parts.² Eocene formations of similar age are found in Colorado (*Telluride*³ and *Poison Canyon*⁴ formations), New Mexico (part of the *Puerco* beds), and elsewhere.

The sites of early Eocene deposition were finally shifted. In so far as the sedimentation was in lakes, the basins may have been filled or warped out of existence, and in so far as it was subaërial, the deformative movements of the time, or the progress of the gradational work of the streams, or both, may have been responsible for the shifting.

2. During the next or *Wasatch stage* of the period, sediment was being deposited over parts of Utah, western Colorado, and Wyoming, and in some other places. The beds of this stage have a maximum thickness of several thousand feet, and are now 6,000 to 7,000 feet above the sea. About 77% of the fossils of this stage are of terrestrial life.⁵

3. The third recognized stage of the Eocene of the west is the *Bridger*,⁶ during which sedimentation was in progress in various places. One area was in the Wind River basin, north of the moun-

¹ Wilder has recently called into question the separability of the *Fort Union* and *Laramie*, in western North Dakota. *Jour. Geol.*, Vol. XII, p. 290.

² For criteria for distinguishing lacustrine and subaërial formations, see Davis, *Science*, N. S., Vol. VI, p. 619, 1897, and *Proc. Am. Acad. Arts and Sci.*, Vol. XXXV, p. 345, 1900.

³ Purington, *Telluride*, Colo. Folio, U. S. Geol. Surv.

⁴ Hills, *Science*, Spanish Peaks and Walsenburg, Colo. Folios, U. S. Geol. Surv.

⁵ Loomis, *Am. Jour. Sci.*, Vol. XXIII, 1907.

⁶ The *Green River* group of Hayden and Powell, the *Wind River* group of Hayden, and the *Dinoceras* beds of Marsh, are included here.

tains of that name, and another, a little later, in the basin of the Green River, both in Wyoming, and in Utah south of the Uinta Mountains. It may have been during this stage, too, that the volcanic tuff (San Juan formation, 2,000 feet and less thick) of the Telluride region was made.¹ This last formation is of interest as an index to the vigor of volcanic action in this region.

4. The *Uinta stage*² followed the Bridger. Deposition was then in progress in southeastern Utah and southwestern Colorado. The deposits occupied a part of the area covered by the Wasatch and Bridger formations, so that these formations are found in superposition, in some places. The Uinta beds now have an altitude of as much as 10,000 feet, though they were probably deposited at a much lower level.³

The northwest. In the northwest there are Eocene formations not definitely correlated with the preceding stages. Thus in northern Oregon, there are late Eocene beds of terrestrial origin (*Clarno* formation, largely volcanic tuff⁴) in the John Day basin, which was the site of aggradation during a large part of the Tertiary. In Washington two thick sedimentary formations (the *Swauk*, early Eocene, 3,500–5,000 feet, below, and the *Roslyn*, 3,500 feet) of Eocene age and non-marine origin, are separated by 300–4,000 feet of basalt. The *Payette* formation of Idaho, said to have been accumulated in a lake formed by the damming of the upper basin of the Snake River by the early lava-flows of the Columbia River region,⁵ is now referred to the Eocene.⁶ Eocene beds of terrestrial or volcanic origin are imperfectly known in many other places west of the Rocky Mountains. The erosion of the Eocene has given rise locally to the topography characteristic of “Bad Lands.”

General considerations. It has been customary to regard the Eocene and later periods as much shorter than those of the Paleo-

¹ Purington, Telluride, Colo., folio, U. S. Geol. Surv.

² Here belong the *Diplacodon* beds of Marsh and the Browns Park group of Powell; Geol. of the Uinta Mountains, pp. 63, 168, 208.

³ It is possible that some of these beds should be referred to the Oligocene.

⁴ Merriam, Jour. Geol., Vol. IX, p. 71, and Bull. Univ. of Cal., Vol. II, p. 285, and Knowlton, Bull. 204, U. S. Geol. Surv.

⁵ Lindgren and Drake, Nampa and Silver City, Idaho, folios, U. S. Geol. Surv.

⁶ Knowlton, op. cit., p. 110.

zoic and Mesozoic; but this conclusion may be questioned. On the basis of thickness, the showing of the system is great, as the formations of Puget Sound, Coos Bay, Ore., and southern California show. In the western interior, too, the thickness of the system is great, if the thicknesses of the beds deposited in the several successive areas of deposition, are added. Furthermore, any just estimate of the duration of the period must take account of the great erosion after the post-Laramie deformation before the deposition of the



Fig. 526.—Section showing the structure of the Eocene in western Oregon. *Eb*, Eocene basalt; *Ep* (Pulaski formation), and *Ec* (Coaledo formation), Eocene. Length of section about 20 miles. (Diller, Coos Bay, Ore., folio, U. S. Geol. Surv.)



Fig. 527.—Section a little south of the last, showing the relation of the Eocene (*Ep*, Pulaski formation) to the Cretaceous (*Km*, Myrtle formation). *as*, amphibolite schist, and *Ps*, Quaternary marine sand. (Coos Bay folio, U. S. Geol. Surv.)

recognized Eocene began. On the physical side, therefore, there is no warrant for the conclusion that the period was short. The faunal developments of the period, too, were such as to make great demands upon time. On the whole, it does not seem improbable that the period was as long as the average of those since the beginning of the Paleozoic.

The conditions requisite for so great thicknesses of terrestrial sediment as occur in the Eocene of western North America are not easily conceived, if the thicknesses are really as great as they have been thought to be. If the areas concerned were in process of more or less continuous warping, the depressions going down as surrounding lands went up, or if troughs or basins of deposition were produced by faulting, the bottoms sinking while their surroundings rose, the conditions for thick sediments would perhaps be met. It has sometimes been urged that these and similar formations are

too thick to be subaërial; but it is not apparent that it is more difficult to account for thick subaërial sediments, under the conditions indicated, than to account for thick lacustrine or marine formations.

The relations of the Eocene beds of the western interior are such as to indicate that both the attitude and altitude of the surfaces in that part of the continent were very different from those which now exist. That region must have been much lower than now, and, locally and temporarily at least, without well-established drainage. The present mountains were certainly not so high as now, though considerable elevations and great relief doubtless existed.

Close of the Eocene in North America. The closing stages of the Eocene were marked by crustal movements in the west, resulting in considerable changes in geography. Such movements had been in progress throughout the period, as has been indicated; but the changes at the close were on a larger scale. The deformative movements seem to have included both faulting and folding. The result was the retreat of the sea along the Pacific coast, the development of new areas of high and low lands, and therefore a shifting of the sites of rapid degradation and aggradation. Outside the Cordilleran region the changes were less.

Along the Atlantic and Gulf coasts the Miocene is in many places unconformable on the Eocene, and it was at the close of the Eocene (or perhaps during the Oligocene) that an island, now included in the peninsula of Florida, was formed. In the Carolinas, and in the western Gulf region, the conformity between the Eocene formations and those classed as Oligocene seems to preclude notable changes of geography along the coast in the southeastern part of the United States at the close of the period.

FOREIGN

Europe. Considerable lakes, estuaries, and perhaps other areas of deposition remained over western Europe within the area from which the sea withdrew, at the close of the Mesozoic era. Later, but still early in the Eocene, submergence of the land set in,

RALPH ARNOLD, JANUARY, 1909.

		Geologic										
		Tertiary										
		Quaternary		Pliocene		Pleistocene		Recent				
Standard California Section	Western Washington	Alluvium	Vashon	Admiralty	Unconformity	Beds at Chinlan Bay, Iduyayude River, Sooke Beds	Unconformity	Beds at Port Blakely, Puca Strait	Unconformity	Beds at Puca Strait, Beau Point, Foca Strait, etc.	Unconformity	Beds at Little Falls (freshwater)
	Central Washington	Alluvium										
	Eastern Oregon	Alluvium										
	Western Oregon	Alluvium										
	Mount Diablo Region	Alluvium										
	Santa Cruz Mountains	Alluvium										
	San Luis Potosi	Alluvium										
	Santa Maria District	Alluvium										
	Coahuila District	Alluvium										
	Ventura County	Alluvium										
Los Angeles County	Alluvium											
San Diego Region	Alluvium											
Cenozoic	Oligocene	San Lorenzo	Unconformity	San Lorenzo	Unconformity	San Lorenzo	Unconformity	San Lorenzo	Unconformity	San Lorenzo	Unconformity	San Lorenzo
		San Lorenzo	Unconformity	San Lorenzo	Unconformity	San Lorenzo	Unconformity	San Lorenzo	Unconformity	San Lorenzo	Unconformity	
	Miocene	San Diego	Unconformity	San Diego	Unconformity	San Diego	Unconformity	San Diego	Unconformity	San Diego	Unconformity	San Diego
		San Diego	Unconformity	San Diego	Unconformity	San Diego	Unconformity	San Diego	Unconformity	San Diego	Unconformity	
	Pliocene	San Pedro	Unconformity	San Pedro	Unconformity	San Pedro	Unconformity	San Pedro	Unconformity	San Pedro	Unconformity	San Pedro
		San Pedro	Unconformity	San Pedro	Unconformity	San Pedro	Unconformity	San Pedro	Unconformity	San Pedro	Unconformity	
	Quaternary	San Pedro	Unconformity	San Pedro	Unconformity	San Pedro	Unconformity	San Pedro	Unconformity	San Pedro	Unconformity	San Pedro
		San Pedro	Unconformity	San Pedro	Unconformity	San Pedro	Unconformity	San Pedro	Unconformity	San Pedro	Unconformity	

allowing the sea to again overspread considerable areas from which it had been temporarily excluded. In western and central Europe the maximum submergence of the Eocene seems to have been accomplished by the middle of the period. Toward its close, the epicontinental waters of the northwestern part of the continent were again restricted. These changes are inferred from the considerable development of fresh- and brackish-water beds in the lower part of the system, of marine beds above them, and of non-marine formations again at the top. Most of the system in central and western Europe is clastic, and the beds are still unindurated, for the most part, and not very thick.

In the south, the Eocene sea spread much beyond the borders of the present Mediterranean, covering much of southern Europe, northern Africa, and part of southeastern Asia. The eastward extension of this sea joined the Indian Ocean, cutting off the southern peninsulas of Asia from the Mainland to the north. A narrow sound east of the Urals probably connected the Arctic Ocean with the expanded Eocene Mediterranean. Out of this extended sea rose many islands, some of which corresponded in position to the Alps, Carpathians, Apennines, and Pyrenees.

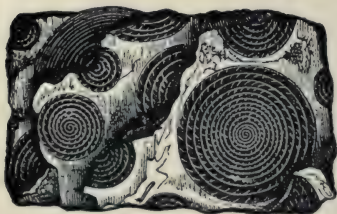


Fig. 528.— A bit of nummulitic limestone.

On the bottom of this great body of water, which should perhaps be thought of as a part of the ocean rather than as a mediterranean sea, limestone was deposited on an extensive scale. Much of it is made up almost wholly of the shells of nummulites (foraminifera, Fig. 528),

and is found from one side of the Old World to the other. Since it is often thick (locally several thousand feet), as well as wide-spread, the sea must have swarmed with foraminifera, and the period must have been long. Hardly anywhere else in the rocks of the whole earth are there indications of such great numbers of organisms of one kind. The Fusulina limestone of the Carboniferous is perhaps most nearly comparable. Some idea of the deformative movements since the Eocene may be gained from

the fact that the nummulitic limestone occurs at elevations of more than 10,000 feet in the Alps, up to 16,000 feet in the Himalayas, and 20,000 feet in Tibet. The principal elevation of the Pyrenees, Carpathian, Caucasus, Thian Shan, and other high mountains of Eurasia, is post-Eocene. In the Old World, therefore, as well as in the New, the greater relief features of the present were undeveloped in the Eocene period.

Other continents. In *Africa*, marine Eocene is known along the northern and western coasts, and in the Soudan. It is known also in *South Australia*, *New Zealand*, and *Tasmania*, though not generally sharply differentiated from the later Tertiary. At the head of the great Australian Bight, there is a thick bed of Eocene chalk. Eocene beds are also known in various islands of the Pacific.

The Tertiary formations of *South America* have not been closely correlated with those of other regions. There is marine Eocene along some parts of the western coast, in Patagonia¹ (Magellanian series), where the beds are usually unconformable on the Cretaceous, probably in Argentina, and along at least a part of the coast of Brazil.² Eocene beds of non-marine origin also occur in Patagonia.³

Eocene beds, not always distinctly separable from the Oligocene, are extensively developed in the *West Indies*, where limestone is the dominant type of rock. In the Caribbean region they occur up to elevations of 5,000 feet on the mainland, and 10,500 feet in Hayti.⁴ It was formerly thought that the Atlantic and Pacific oceans connected freely across Panama during the early Tertiary, but the work of Hill renders it doubtful whether there were more than shallow and restricted connections in the Eocene, and whether there was connection of any sort later.

General geography of the Eocene. Eocene geography was very different from that of the present time, and the differences were

¹ Hatcher, *Am. Jour. Sci.*, Vol. IX, 1900, pp. 97-99; also Vol. IV, 1897, pp. 334-337.

² Branner, *Bull. Geol. Soc. Am.*, Vol. XIII, Stone Reefs of Brazil. *Mus. of Comp. Zool.*, Bull. 44, pp. 27-53.

³ Ameghino, *L'age des Formations Sedimentaries de Patagonia*, *Anales de la Sociedad Cientifica Argentina*, 1903.

⁴ Hill, *Geological History of the Isthmus of Panama and Portions of Costa Rica*. *Bull. Mus. of Comp. Zool.*, Cambridge, 1898.

perhaps even greater than has been indicated. It has been conjectured that North America was connected with Asia on the west, via Alaska, and with Europe on the east, via Greenland and Iceland. Land seems to have failed of making a circuit in the high latitudes of the north only by the strait or sound east of the Urals. In the southern hemisphere, it has been surmised that Antarctica was greatly extended, connecting with South America, Australia, and possibly with Africa, and that Africa and South America were connected across the Pacific¹ from some earlier time until after the beginning of the Eocene. The basis for these conjectures is found in the distribution of life at that time, as shown by fossils.

If these conjectured extensions of land were real, it will be seen that the division of land and water in the northern and southern hemispheres was far less unequal than now, and that the land was massed in high latitudes to a greater extent than at present, while tropical seas were more extensive. If extensive polar lands were the cause of glacial periods, as has been suggested, the geographic conditions of the Eocene were favorable in the extreme, if the relations sketched above were the real ones. In spite of this, the climate of the period seems to have been genial, and less markedly zonal than now.

Close of the Eocene. During the later part of this period, and at its close, there were some notable deformations in Southern Europe. The initiation of the Pyrenees, and of some of the mountains farther east, is assigned to this time, and the distribution of the later formations, when compared with the distribution of the Eocene, shows that changes of a less pronounced type were in progress. The greater deformations which express themselves in the mountains of Southern Europe are post-Eocene, and most of them considerably later than the close of the Eocene.

THE EOCENE LIFE

The Transition from the Mesozoic

Four salient features marked the transition of life from the Mesozoic to the Cenozoic: (1) Among marine animals, nearly all

¹ Neumayr, *Erdegeschichte*, Bd. II.

Cretaceous species were replaced by new ones; (2) among land plants so many species lived over as to make the plane of division between the Mesozoic and Cenozoic very difficult of location; (3) the great saurians almost disappeared, and most other reptiles showed profound changes; and (4) placental mammals appeared in force, and promptly took a leading place. The combination is unique, in that, while half the land life joined with the sea life in undergoing a profound transformation, the other half did not participate notably in the revolution. In explanation of profound transformations of epicontinental marine life, appeal has been made repeatedly to the withdrawal of the sea, to the extension of the land, and to climatic changes incident to deformative movements; and this appeal may be renewed so far as the change in the sea life is concerned. The withdrawal of the sea after the Cretaceous period seems peculiarly well fitted to explain the great change in epicontinental sea life, because of the great restriction of the area of shallow water. The increase of the land and the establishment of new land connections at the same time might well have caused the existing vegetation to spread and flourish, if the climate remained congenial; but why did the land faunas not respond in like manner? Closely connected with this problem is the sudden rise of the mammals.

It is an open question whether the placental mammals of North America and Eurasia arose from non-placental mammals which lived in these continents earlier, or whether they were immigrants. No satisfactory evidence of a transition from non-placental mammals has been produced, and the strength and suddenness of the placental development suggest invasion from some quarter where their evolution had reached an advanced stage. The deformative movements which closed the Cretaceous period and inaugurated the Eocene quite certainly made many new land connections, and furnished the conditions for an invasion, if mammals in sufficient variety and numbers were awaiting the opportunity.

The rise of placentals may have caused the downfall of the reptiles, though this cannot be affirmed. The habit of bringing forth relatively mature offspring, and of nourishing and protecting them, gave the mammals an immense advantage. To this advantage were added superior agility and higher brain power. It

is not surprising, therefore, that the rise of the mammals drove the clumsy, affectionless, small-brained reptiles either into extinction, or to the assumption of new and smaller forms.

The angiosperms may have been a factor in the placental dispersion, through the fact that they are a staple source of food of the mammals. It may have been the spread of this flora from its originating tract, until it came into contact with the primitive placentals in their originating tract, that caused the rapid spread and evolution of the latter.

The Vegetation

In plant history, the Eocene was not the dawn of the recent, for the great change from medieval to modern plants took place in the Comanchean period. The Eocene was not even the period of any radical innovation. There was, however, much progress toward living species, and toward present adaptations of plants to climate, soil, and topography, and to each other.

Among the plants of the earliest known Tertiary flora of Europe were oaks like those of the present elevated districts of warm temperate zones. With them were willows, chestnuts, laurels, ivies, aralias, etc., which have been likened to the flora of southern Japan.

The flora of the Denver beds (p. 752), contains figs, poplars, laurels, magnolias, and many ferns. The early Eocene flora of southern Canada¹ included similar forms, together with oaks, beeches, etc., a flora indicating a temperate climate.

The Middle Eocene flora of England records a flora "the most tropical in general aspect which has yet been studied in the northern hemisphere,"² while a later flora "suggests a comparison of its climate and forests with those of the Malay Archipelago and tropical America." The Mid-Eocene series of America in temperate latitudes contains palms and bananas, mingled with many other trees of similar climatic significance.

¹ Penhallow. Tertiary Plants of British Columbia, Can. Rept. of Mines, 1908.

² Geikie, Text-book of Geology, 3d ed., p. 974.

*The Land Animals*¹

The undifferentiated nature of the early Eocene mammals. It is difficult to carry our conceptions of mammals back to the Eocene prototypes, without carrying with them distinctions which did not then exist. The earliest Eocene mammals were much more primitive than those of the Middle Eocene, and their rapid convergence backward seems to point to some set of conditions which caused a rapid advance of the class at this time whatever their previous history. The coming into a new domain of rich and varied conditions whether by immigration or indigenous development, may be safely included among these conditions.

The mammals of the earliest Eocene, as now understood, included several vaguely differentiated groups, in which existing orders were foreshadowed rather than represented. The herbivores were foreshadowed by the *Condylarthra*, and the carnivores by the *Creodonta*; but the two were not sharply differentiated. Both were five-toed plantigrades, whose phalanges had horny coverings that were neither hoofs nor claws. Ancestral *edentates*, *insectivores*, *rodents*, and *lemuroids* seem to have been represented in an obscure fashion.

The evolution of the mammals was so rapid that before the close of the Eocene, the *Herbivora* (*Ungulata*), *Carnivora*, *Edentata*, *Insectivora*, *Rodentia*, *Quadrumania*, *Cetacea*, and *Sirenia*, and probably the *Cheiroptera* were distinctly defined (see p. 945). None of the present *genera*, however, are known as early as the Eocene. When it is recalled that the name Eocene was founded on the presence of some few *species* of living invertebrates, the great difference between the stage of their evolution and that of the mammals may be realized. In general the mammalian faunas of the early Eocene were closely similar to those of Western Europe, while in the middle and late Eocene there seems to have been faunal separation from Europe.²

The main herbivore line. While the condylarths and creodonts were near each other at the beginning of the period, the hoofed

¹ For references to important literature on the American Tertiary Mammalia, see the authors' larger work, Vol. III, p. 228.

² Osborn, Bull. 361, U. S. Geol. Surv.

herbivores and the clawed carnivores soon became distinct. The condylarths (Fig. 529) were small generalized forms with five toes and forty-four teeth, not yet developed into the true herbivorous type. They have lived on till now without radical change, but one branch, adapted to forests and marshes, seems to have diverged early, and to have given rise to the ungulates. In the course of the period many of them became fitted for life on grassy plains.



Fig. 529.— A primitive ungulate or condylarth of the Wasatch epoch; *Phenacodus primævus* Cope, about $\frac{1}{13}$ natural size (about the size of a tapir), from Big Horn basin, Wyoming. (Cope.)

To this end, there was a progressive abandonment of the flat, heavy, palmate form of foot, and the acquisition of the light, springy, digitate habit, adapted to a quick start and swift flight. At the same time hard hoofs, and powerful grinding teeth were developed. The evolution of hoofs and grinding teeth has been thought to be connected with the prevalence of grassy plains, the firm turf of which is in contrast with the soft soil of forest and marsh. Grasses also are much associated with dry and even semi-arid grounds, and dessication intensifies the firmness of the bottom, and gives additional occasion for the hoof. The forests perhaps helped to preserve a section of the evolving order in its more primitive form.

Back of these influences lay the physical conditions that promoted them. In western America, where the evolution is best

known, the lakes and rivers were undergoing changes. If these followed the methods of to-day, they left behind them, as they shrank or shifted, borders of grassy or sedgy ground which, on fuller drainage, often became prairie. Such changes were suited to the evolution of herbivorous prairie life, and this in turn must have invited its appropriate contingent of predaceous animals. If these considerations are valid, the prime factors in the evolution of the ungulates were (1) an undifferentiated plastic animal group susceptible of modification; (2) a plant group (grasses and fodder-furnishing angiosperms) affording appropriate food for the new type; and (3) the shrinkage and shifting of lakes, marshes, and lodgment plains, and the drying up of the plains of the continent, resulting in prairies whose hard turf favored the development of foot and limb modification in the interest of speed.

The era of bulk and heavy armor, such as had been possessed by the reptiles, had passed, and an era of agility and dexterity had begun. No small factor in this progress was the increase in intelligence indicated by the larger brains. The lighter and more agile frame was accompanied by the development of smaller, simpler, but more effective weapons of attack and defense. Nevertheless size continued to be important, and some species in almost every sub-order reached and passed the limit of bulk-advantage, and then declined.

In the course of the early evolution strange forms appeared, and soon became extinct. Among them were the *Dinocerata* (Fig. 530), grotesque monsters whose skulls were armed with three pairs of protuberances, perhaps horn cores, and a pair of enormous canine teeth or tusks projecting below (at least in the male), and an extravagant attempt at armature on both upper and nether sides. Their brains were smooth and singularly small for such ponderous bodies. In them, brute mass and low brain-power seem to have reached their climax among mammals.

The divergence of ungulates into odd- and even-toed. Early in the Eocene, the hoofed animals began to diverge into odd-toed (*perissodactyls*) and even-toed (*artiodactyls*) types. In the former, the main line of support is in the axis of the middle toe; in the latter, between the third and fourth toes. In the course of time

the lateral toes fell out of use and were atrophied. The first class reached its extreme type at length in the horse, and the second in our cloven-hoofed cattle; but these perfected types were not attained in the Eocene, for the evolution of the perissodactyls did not pass beyond three-toed forms in the Eocene.

The horse has become a classic example of evolution. The earliest recognized form was the *Hyracotherium* (Fig. 531), whose equine characters were obscure. *Pachynolophus* represented a

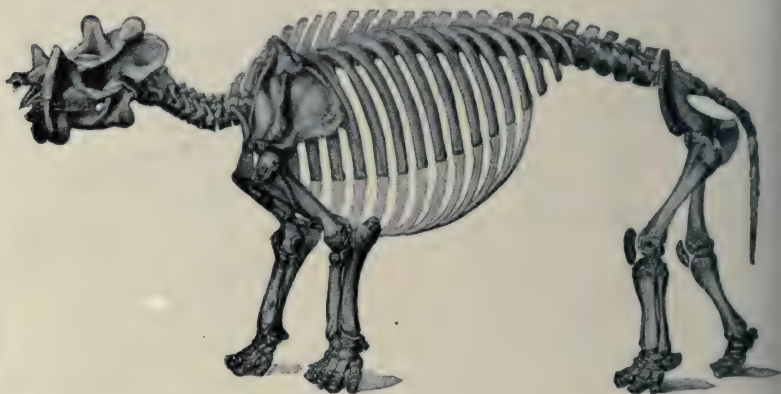


Fig. 530.—*Dinoceras mirabile*, restoration of skeleton by Marsh; about 13 feet long, Middle Eocene, Wyoming.

slight advance, and the *Orohippus* (*Epihippus*) a greater one. The latter was four-toed (three functional) in front and three-toed behind, and the limbs and teeth were slightly modified in the direction of the horse. These forms were about the size of a small dog, and as much canine as equine in appearance. The evolution continued through the remaining periods of the Tertiary, true horses appearing in the Pliocene. The primitive Eocene forms lived both in Europe and America, and the evolution followed similar lines in the two continents.

The rhinoceros family appears in the record in the later part of this period, but had its development chiefly in the next.

Artiodactyls emerged from their generalized beginnings more slowly. *Suina* (pigs, peccaries, hippopotamuses) were represented

in the Bridger epoch by a primitive small hog with strong canine teeth of somewhat carnivorous aspect. Strangely enough, *Tylopoda* (camels, llamas) seem to have their beginnings on the American continent in the middle and later Eocene, and to have flourished here until the Pliocene. Then, having previously sent a branch to South America to evolve into llamas and vicunas, and another into the Old World to become the present camels, the tribe died out in its primitive home.

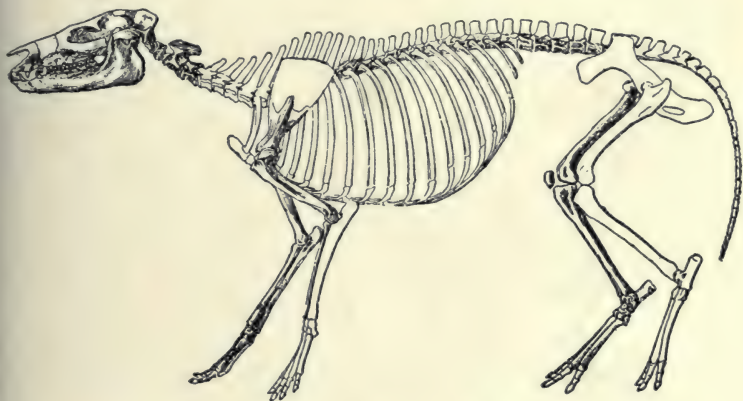


Fig. 531.—An early ancestor of the horse family, *Hyracotherium* (*Protorohippus*) *venticolum*, from the Lower Eocene (Wind River formation) of Wyoming; about $\frac{1}{4}$ natural size. (Cope.)

The carnivore line. It has been thought by some paleontologists that the *creodonts* were more primitive than the *condylarths*, and that the latter diverged from the former, as also the *edentates* and the *rodents*. If this is so, it gives the *creodonts* the central position among the primitive mammals. The *creodonts* ranged throughout the whole period and passed into the next, gradually giving way meanwhile to their own more progressive descendants. They were common in America and in Europe, and they lived in South America. Modern types began to emerge definitely from the ancestral forms toward the end of the period. *Patriofelis* ("the father of cats," a name not to be taken too literally) of the Bridger epoch, presented a suggestive combination of characters, some features resembling

those of cats, and others those of seals. Some species seem to have been aquatic. Primitive representatives of the dog family appeared in Europe late in the period.

Edentates, rodents, and insectivores. The similarity of the ancestral *edentates* to the condylarths and creodonts of the earliest Eocene seems to imply that the three orders had but recently diverged from common ancestors. The primitive *rodents* of the early

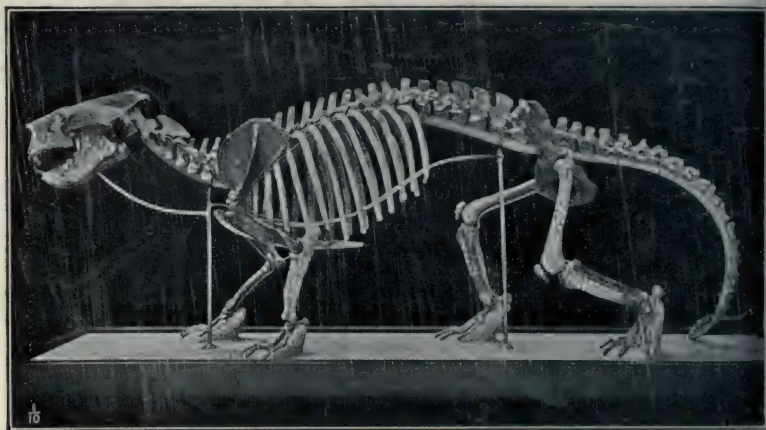


Fig. 532.—Mounted skeleton of *Patriofelis*, a Creodont from the Middle Eocene of Wyoming; $\frac{1}{18}$ natural size. (Osborn).

Eocene had incisors which had just begun to assume their specific gnawing functions. By the middle of the period, rodents became a notable element in the fauna, the *Tillotherium* of the Bridger formation having finely specialized incisors (Fig 533). The primitive squirrel appeared in Europe in the latter part of the period. Even to-day, the rodents retain many primitive characters, and since the Miocene they have undergone few radical changes. Their derivation is not yet determined.

Most living families of *insectivores* can be traced back to the Eocene. They still retain many primitive characters, and are the least altered of the great mammalian branches.

The non-placental mammals. During the Eocene, early forms of the opossum appeared in both the Old and New World. They retained this wide distribution until the Miocene, when they disappeared in Europe, but they have persisted in North and South America to the present time. It is a singular fact that the monotremes, the lowest of the mammals, are not known to have appeared until after the Tertiary.

The primates (*Quadrumana*). No traces of apes have been found in the Eocene, but representatives of the lower primates, the

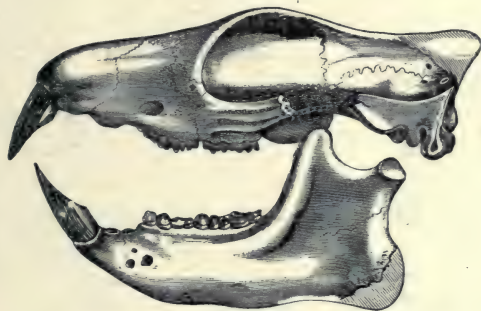


Fig. 533.—The skull and jaw of a large Eocene rodent, *Tillolotherium fodiens* Marsh, from the Bridger formation, Wyoming; about $\frac{1}{6}$ natural size.

lemuroids, appeared in the Wasatch epoch in America, and in a similar horizon in Europe. This is the more notable, as the lemurs are now confined to Madagascar, Africa, and southern Asia. The lemurs show many affinities with the insectivores, and were possibly derived from them. The apes are probably descended from the early lemuroids.

The mammals go down to sea. Just as the land reptiles of Mesozoic times took to the sea by choice or necessity, so did the mammals in their day. Thus arose cetaceans (whales, dolphins, porpoises), sirenians (manatees, dugongs), and pinnipeds (seals, sea-lions). In parts of Alabama, vertebræ of primitive whales (*Zeuglodon*s) were originally so abundant as to attract popular attention and call forth legends of divers catastrophes.

Birds. Fossils of ancestral gulls, herons, flamingoes, albatrosses, buzzards, falcons, eagles, owls, woodcock, quails, plovers, and ostrich-like, flightless birds of great size, with not a few forms of doubtful interpretation, have been found, showing great deployment of this class.

Reptiles and amphibians. One of the greatest contrasts in geological history is found in comparing the size, power, and multitude of the Cretaceous land reptiles with those of the Eocene. Of the great saurians, only a few lived on into the Eocene and they did not live long. Land reptiles seem to have become rare early in the period. There were turtles on both land and sea, and some of them attained large size. There were crocodiles which belonged about equally to land and water; also snakes, some of them large. Amphibians were present, but apparently not abundant.

The insect life. There has been little important change in the insect world since the beginning of the Cenozoic era. Few new families have appeared, though the genera and species have changed.¹

Marine Life

The name Eocene, founded upon the presence of a small percentage (less than 5%) of *living* species among the marine invertebrates, implies their stage of advancement. Not only were the existing orders, families, and genera established, with some exceptions, but even the present species had begun to appear. The changes that follow from this time on are valuable as criteria of correlation, climate, migration, and other elements of the later history, but they do not record profound biological transformations. They stand in striking contrast with the radical and rapid evolution of the mammals.

Geologically, the most striking feature of the marine Eocene life was the extraordinary abundance and size of the *foraminifers* (Fig. 534). Reference has already been made to the prodigious abundance of the *nummulites*. *Gastropods* and *pelecypods* of modern types were very numerous, but *cephalopods* were much less important than in the Cretaceous. *Sea-urchins* continued to be

¹ Mono. XXI, U. S. Geol. Surv., 1893, p. 1.

abundant, the *corals* had taken on modern forms, and *decapods* were rising in importance.

The American Eocene faunas¹ were rather pronouncedly provincial, though some species have a rather wide range. So pronounced is the provincial character of the faunas, that much difficulty is experienced in making correlations between formations

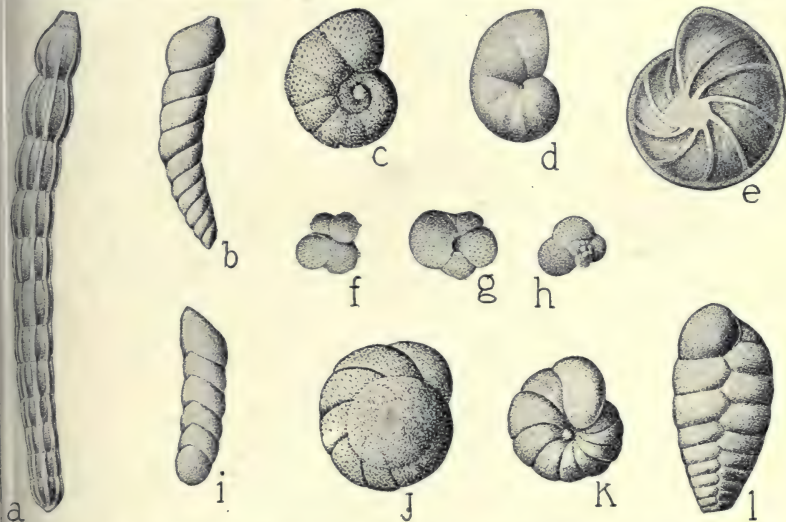


Fig. 534.—EOCENE FORMINIFERA. *a*, *Nodosaria bacillum* DeFrance; *b*, *N. communis* (d'Orbigny); *c*, *Anomalina ammonoides* (Reuss); *d*, *Cristellaria gibba* d'Orbigny; *e*, *C. radiata* (Bornemann); *f*, *g*, and *h*, *Globigerina bulloides* d'Orbigny; *i*, *Vaginalina legumen* (Linné); *j*, *Discorbina turbo* (d'Orbigny); *k*, *Truncatulina lobatula* (Walker and Jacob); *l*, *Textularia subangulata* (d'Orbigny). Magnified 8 to 40 times. (Maryland Geol. Surv.)

along different parts of the Atlantic and Gulf coasts, and greater difficulties arise in regions more widely separated. The variations are, however, variations of detail, not of broad features.

¹ W. H. Dall, Trans. Wagner Free Inst. Sci., Vol. III, 1890-1900; Bull. 141, U. S. Geol. Surv., 1896; W. B. Clark, Md. Geol. Surv., Eocene volume, 1901; R. M. Bagg, Bull. 141, U. S. Geol. Surv., 1896; A. Heilprin, Proc. Acad. Nat. Sci. Phil., Vol. XXXI, 1879; Vol. XXXII, 1880; and Vol. XXXIII, 1881; Jour. Acad. Nat. Sci. Phil., Vol. IX, 1884; T. W. Vaughan, Bull. 141, U. S. Geol. Surv., 1896; Mon. XXXIX, U. S. Geol. Surv., 1900; T. W. Stanton, 17th Ann. Rept., U. S. Geol. Surv., Pt. I, 1895-6; G. D. Harris, Am. Pal. Bull., Vols. I and II.



Fig. 535.—EOCENE MOLLUSKS. *a-h*, Gastropods: *a*, *Fusus* (?) *interstriatus* Heilprin; *b*, *Mitra potomacensis* Clark and Martin; *c*, *Pleurotoma tysoni* Clark and Martin; *d*, *P. potomacensis* Clark and Martin; *e*, *Scala potomacensis* Clark and Martin; *f*, *Tornatella bella* Conrad; *g*, *Turritella mortoni* Conrad; *h*, *Lunatia marylandica* Conrad. *i-w*, Pelecypods: *i*, *Glycymeris idoneus* (Conrad); *j*, *Dosiniopsis lenticularis* (Rogers); *k* and *l*, *Venaricardia marylandica* Clark and Martin; *m* and *n*, *Corbula aldrichi* (Continued at bottom of page 797.)

Climate. The marine fauna of the Pacific coast,¹ and the flora² as far north as Puget Sound, point to a subtropical climate.

THE OLIGOCENE FORMATIONS

In North America. As already stated, formations corresponding to the Oligocene of Europe have not usually been differentiated, in North America. The differentiation may be justified on paleontological grounds, if it is desirable to make the classification for this country conform closely to that of Europe.³ If the Oligocene is to be recognized, certain formations along the Atlantic and Gulf coasts, formerly regarded as late Eocene or early Miocene, should be classed as Oligocene. In the Gulf region the Vicksburg (below) and Grand Gulf formations⁴ of Alabama, Mississippi, and Louisiana, and the Fayette⁵ formation of Texas, belong to this category.

The early Oligocene is represented generously about the Caribbean sea, where its association with the Eocene is generally close,⁶ and its separation from the Miocene distinct. This is in keeping with the phenomena of the Gulf States. Limestone is the dominant type of rock in the Antillean region.

The Oligocene stage is also recognized among the terrestrial deposits of the western part of the continent. The *White River* formation, now classed as Oligocene, occupies an extensive area in northeastern Colorado, southwestern Wyoming, western Nebraska (Brule and Chadron formations⁷), and South Dakota, and perhaps

¹ Arnold, Jour. Geol., 1909.

² Knowlton, Tacoma, Wash. Folio.

³ For table of Oligocene formations, see Dall, 18th Ann. Rept., U. S. Geol. Surv., Pt. II.

⁴ The classification of the Grand Gulf formation is in dispute. Some of the beds described under this name are probably younger than Oligocene; see Smith and Aldrich, Science, N. S., Vol. XVI, p. 836, and Vol. XVIII, p. 26.

⁵ Penrose, Geol. Surv. of Texas, 1st Ann. Rept.

⁶ Hill, Geology and Physical Geography of Jamaica, and Geological History of the Isthmus of Panama and portions of Costa Rica. Bull. Mus. Comp. Zool., Vols. XXVIII and XXXIV respectively.

⁷ Darton, Camp Clarke, Scotts Bluff, Edgemont, and Oelrichs folios, U. S. Geol. Surv.

Meyer; *o* and *p*, *Protocardia levis* Conrad; *q*, *Ostrea compressirostra* Say; *r*, *Modiolus alabamensis* Aldrich; *s*, *Lucina aquiana* Clark; *t*, *Leda parilis* (Conrad); *u*, *Crassatellites alaformis* (Conrad); *v*, *Nucula ovula* Lea; *w*, *Pecten choctawensis* Aldrich. (Maryland Geol. Surv.)

in Kansas.¹ In the light of present knowledge, it seems probable that all phases of land aggradation, lacustrine, fluvial, and eolian, are represented in this formation.² Even thin beds and lenses of limestone and volcanic ash enter into it. The formation is said to have originally covered most of the Black Hills region, and possibly all of it.³ Remnants are now found up to elevations of more than 6,000 feet, and the highest points of the hills are but little higher. The *Florissant* beds in South Park, Colo., consisting largely of



Fig. 536.—Chimney Rock, a detail in the Bad Lands of the White River country. The base of the column is Brule clay. (Darton, U. S. Geol. Surv.)

volcanic ash, and famous for their extraordinary number of fossil insects, are classed as Oligocene. So also are some of the beds of the John Day Basin of Oregon,⁴ unconformable above the Eocene. Marine Oligocene beds are found in California, Oregon, Washington, British Columbia, and Alaska, at least,⁵ but at many points on the Pacific coast, the record of the period is found chiefly in the unconformity between the Eocene and the Miocene. The lands

¹ Adams, *Am. Geol.*, Vol. XXIX, p. 303.

² Fraas, *Science*, Vol. XIV, N. S., p. 212, and Matthew, *Am. Nat.*, Vol. XXXIII, p. 403, 1899.

³ Darton, 19th Ann. Rept., U. S. Geol. Surv., Pt. IV; 21st Ann. Rept. U. S. Geol. Surv., II.

⁴ Dall, 19th Ann. Rept., U. S. Geol. Surv.; Merriam, *Jour. Geol.*, Vol. IX, pp. 71-72, and *Bull. Univ. of Cal.*, Vol. II, pp. 270 et seq.

⁵ Arnold, *Bull.* 321, U. S. Geol. Surv.

which contributed the Oligocene sediments were mostly low. Shale is the dominant rock of the series, which is much thinner than the Eocene.

Considerable geographic changes occurred during the Oligocene, or at its close, especially in the Gulf and Caribbean regions,¹ where



Fig. 537.— Oligocene Bad Lands of South Dakota. (Williston.)

the Oligocene (early Oligocene) is commonly conformable on the Eocene, and unconformable beneath the Miocene.

FOREIGN

Europe. The Oligocene is more distinctly differentiated from the Eocene in Europe than in most parts of America. Toward the close of the Eocene, the epicontinental sea of northern Europe was greatly restricted, but considerable areas stood so near sea-level that slight changes served to greatly diminish or extend the epicontinental waters.

¹ See references to the writings of Hill under Eocene.

The oldest Oligocene deposits of central and western Europe are largely of terrestrial, fresh- and brackish-water origin. Local deposits of salt, gypsum, and coal are suggestive of the physical conditions at various times and places. The Oligocene of southern Europe is chiefly marine, but in the upper part of the series, lake and marsh deposits are not rare. In Italy it has been estimated to have the extraordinary thickness of nearly 12,000 feet.

In Europe, as in North America, there were considerable igneous eruption, during the Tertiary, and especially during the Oligocene. The results are to be seen in Bohemia, where there is much igneous rock; in northern Ireland and western Scotland, where outpourings of lava probably made great plateaus, of which some of the adjacent islands are remnants; in Iceland, and in the Vienna basin. Between eruptions, vegetation grew in the marshes and shallow lakes and over the surface of the lava. The substance of this vegetation is locally (Faroes, and Iceland) preserved in the form of coal between the lava beds. Some of the lakes of France seem to have been obliterated by volcanic action.

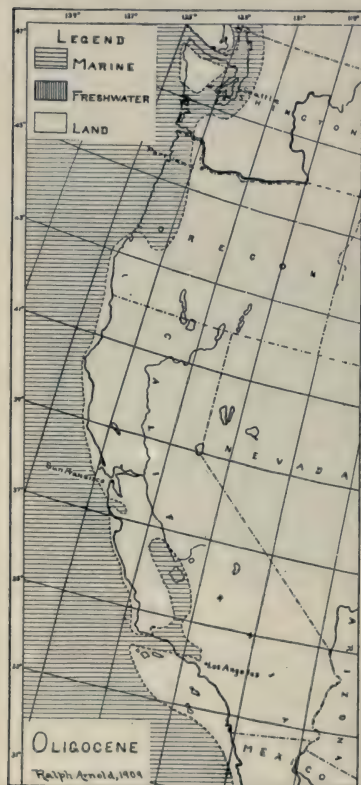


Fig. 538.—Map showing supposed distribution of land and water on the Pacific coast of the United States during the Oligocene epoch. (Ralph Arnold.)

Amber. One of the peculiar accessories in the Lower Oligocene is the amber of northern Germany, principally in the vicinity of Königsberg. While amber in small quantities is found in Sicily and a few other places, that of the Baltic region is more abundant than that of any other part of the earth, so far as now known.

Amber is fossilized resin, apparently from certain varieties of coniferous trees. Its original position in the Baltic region appears to be in certain glauconitic beds of a clayey nature, but parts of this formation have been worn by the waves, and the amber distributed. Some of that which finds its way into commerce is picked up on the Baltic shore, while some is taken from the beds in which it was originally entombed. One of the interesting features of the amber is the fact that it frequently contains insects. The insects seem to have alighted upon the resin while it was soft, and to have become completely immersed in it, and perfectly preserved. About 2,000 species have been found thus embedded.

Considerable deformative movements made themselves felt in Southern Europe at or about the close of the Oligocene, as in the Balkan and Carpathian Mountains.¹

Other continents. In other continents, the Oligocene has not been generally differentiated, but it is known in northern Africa and in Patagonia,² where it is partly marine and partly non-marine.

THE LIFE OF THE OLIGOCENE

The vegetation. The mixed evergreen and deciduous forests of the Oligocene were similar to those of the Eocene, especially in Europe, where palms continued to be abundant and varied, growing even in north Germany. They seem to have become rare, however, in the United States, for in the Florissant sediments, which are rich in plant fossils as well as insects, palms are barely represented. The Florissant fossils show a variety of angiosperms, widely distributed through the several orders that are now found in the latitude of the middle and southern states.

The land animals. All the species of *insects* of the Florissant beds³ (over 700) are extinct. This seems to indicate that although the types had all become modern, the species continued to change with relative rapidity. Fish fossils are abundant in the same beds.

¹ Willis. Carnegie Institution Year book 4, 1905.

² Hatcher, See references to this region under Eocene, and especially Geol. Mag., 1902, p. 136.

³ The Tertiary Insects of North America, U. S. Geol. Surv. Ter., Vol. XIII, 1890; Mon. XXI and XL, U. S. Geol. Surv., 1893 and 1900.

Mammals continued their rapid evolution without interruption, and perhaps even with some acceleration. The *Carnivora* came into clear definition, and were represented in the White River beds by ancestral dogs, cats, coons, and weasels, while some creodonts remained. Rodents were represented by squirrels, beavers, pocket-gophers, rabbits, and mice. Among perissodactyls, the

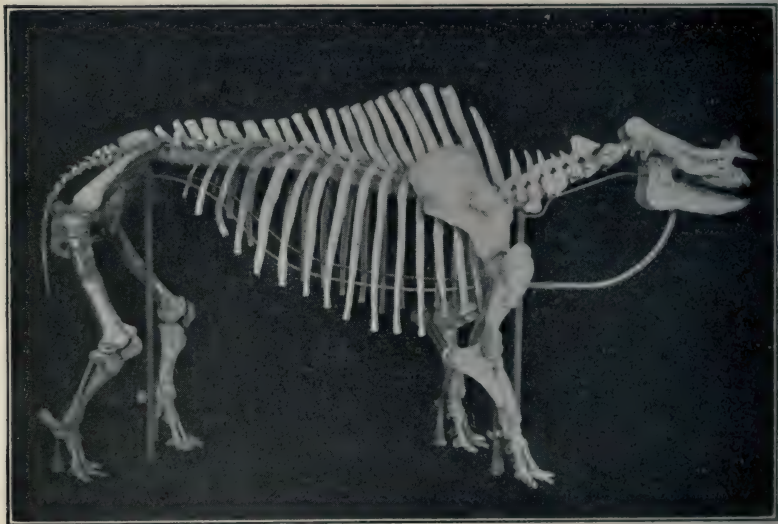


Fig. 539.—*Titanotherium validum* Marsh, photograph of a mounted specimen in the Carnegie Museum. (Holland.)

rapidly developing horse family was represented by *Mesohippus* and *Anchippus*. The *rhinoceros* tribe had deployed into three branches, one a lowland form, ancestral to the existing family, another aquatic, and a third an upland, horse-like, running form. The tribe had a cosmopolitan range.

The *titanotheres*, an erratic branch of the odd-toed ungulates which arose late in the Eocene, reached their climax in the Oligocene (White River), and then disappeared. They were intermediate in proportions between the rhinoceros and the elephant, and were distinguished by a long, depressed skull armed with a pair of

horns near the extremity of the nose, as were their kin the rhinoceroses, but placed transversely, as in the ox (Fig. 539). They reached some fourteen feet in length and ten in height. They were American and apparently rather local. Another odd type were the elotheres, which appeared in North America in the White River



Fig. 540.—An interpretation of the general appearance of the elotheres, or giant pigs, of the White River epoch, drawn by Charles R. Knight under suggestions from Osborn and Scott, based on a skeleton in the Princeton Museum. (From drawing in American Museum of Natural History. Copyrighted by the Museum.)

stage, and continued into the Miocene. An interpretation of their general appearance is shown in Fig. 540.

Artiodactyls were prominent, represented by various extinct forms, and by ancestral peccaries, camels, ruminants, and the singularly specialized horned and tusked *Protoceras*. *Protoceras* was remotely related to the deer family, and was profusely and strangely horned, as though in diminutive mimicry of the

Dinocerata. The animal was about the size of a sheep, and had but a short career.

The ruminants seem to have been introduced or foreshadowed by the *Tragulidæ* (chevratins), now represented in Farther India by a slender little ruminant, isolated and scarcely known, the *Tragulus*, "the scarcely altered survivor of a great tribe which flourished abundantly in Europe, and less so in North America, before the typical and fully differentiated ruminants had made their appearance"¹ Many of the foregoing types were present also in Europe, where there were types not now known in America.

The marine life. If the Vicksburg formation is regarded as Oligocene, the general aspect of the Eocene sea life remained unchanged. In the later stages of the Oligocene, provincialism became pronounced and the correlation of beds, even in the same province, has been the subject of much difference of opinion.² By this time, the foraminifers had declined greatly, and the fauna was overwhelmingly molluscan.

On the Pacific coast, the Oligocene fauna shows closer relation to the Miocene fauna than to that of the Eocene, and suggests a climate transitional between that of the Eocene and that of the Miocene.³

¹ A. Smith Woodward, *Vert. Pal.*, p. 360.

² Maury, *Bull. Am. Pal.*, No. 15, Cornell Univ., 1902.

³ Arnold, *Jour. Geol.*, Vol. XVII.

CHAPTER XXVIII

THE MIOCENE PERIOD¹

The distribution of the Miocene system (Fig. 541) shows that the geography of the North American continent was much the same during the Miocene period as during the Eocene, the sea covering no more than narrow borders of the present land. The slight emergence of the coastal borders after the Eocene (or early Oligocene) was followed by a slight submergence of the same regions during the Miocene. In the western interior, wide-spread terrestrial aggradation of all phases continued, but the sites of principal deposition differed somewhat from those of the preceding period.

The Atlantic coast. In its surface distribution, the Miocene sustains the same relation to the Eocene that the latter does to the Cretaceous, though it sometimes overlaps the Eocene, completely concealing it. There is generally a slight unconformity between the Miocene and the Eocene (or Oligocene). Like the other formations of the Coastal Plain, the Miocene beds dip seaward and are concealed by younger beds some distance to landward from the present shore line. The general relations are indicated by Fig. 499. The system originally extended inland far beyond its present border, as shown by numerous outliers.

The Miocene of the Atlantic coast is composed chiefly of unconsolidated sand, clay, and shell marl. In places, diatomaceous earths are found in beds of such thickness (30 or 40 feet) as to be valuable commercially. In New Jersey,² the Miocene reaches a

¹ For general summary of literature on the Miocene (Miocene and Pliocene) prior to 1892, see Dall and Harris, Bull. 84, U. S. Geol. Surv. The bibliography up to 1896 is found in the 18th Ann. Rept., U. S. Geol. Surv., Pt. II (Dall).

² Reports of the State Geologist of New Jersey, especially Report of 1892.



Fig. 541.— Map showing the distribution of the Miocene formations in North America. Conventions as in preceding maps.

thickness of 700 feet, in Maryland,¹ about 400 feet, and in North Carolina it is still thinner.

The Miocene of the Atlantic coast is generally called the *Chesapeake* formation. This was formerly regarded as Upper Miocene, the former Lower Miocene being now classed as Oligocene. The fauna of the Chesapeake series has been interpreted to indicate a climate somewhat cooler than that which had preceded.

The Gulf coast. The Miocene of the Gulf coast sustains the same general relations to older formations as that of the Atlantic, except that it is not known to be so generally unconformable on the beds below. Excluding the beds classed as Oligocene, the Miocene of this region has but slight thickness. In Florida, the Miocene limestone has been changed locally to lime phosphate.² The alteration appears to have been effected through organic matter, especially the animal excrements accumulated about bird, seal, and perhaps other rookeries. The organic matter furnished the phosphoric acid, which, carried down in solution, changed the carbonate of lime to the phosphate. The phosphate has been extensively used as a fertilizer for soils. The Miocene is represented in Alabama and adjacent stages (the *Pascagoula* formation) and in Texas (*Oakville* beds), where both marine and non-marine phases are present. Much of the oil of Texas and Louisiana (Beaumont, Sour Lake, Saratoga, Jennings, etc.) comes from dolomized limestone which overlies Eocene (or Oligocene) clays, and is probably Miocene.³

The Pacific coast.⁴ At the beginning of the period, the sea encroached upon the Pacific coast, covering considerable areas which were land during the Oligocene time. It flooded the southern part of the central valley of California early in the period, and later the northern part as well. At about the beginning of the period, faulting seems to have affected considerable parts of California, and some of the planes of movement at that time have served as planes of movement until now. This was the time of

¹ Clark, Maryland Geol. Surv., Vol. I, and volume on the Miocene, 1904.

² Penrose, Bull. 46, U. S. Geol. Surv.

³ Hayes, Bull. 213, U. S. Geol. Surv., p. 346.

⁴ Arnold, Ralph, Jour. Geol., Vol. XVII.

the first definitely recognized movement along the great *earthquake rift* of California. Though subsidence was the rule in central and southern California, local fault-blocks seem to have had notable elevation.

The Miocene history of the Pacific coast is divided into two somewhat distinct epochs, the earlier and the later, the separation being marked by diastrophism and vulcanism.

The lowest (*Vaqueros*) formation of the early Miocene in southern California is largely clastic, but later beds (*Monterey*) contain a large amount of diatomaceous material, and the diatomaceous beds are an important source of oil.¹ The amount of silicious material ascribed to diatoms is prodigious, and only seems credible when the extraordinary rate of reproduction of diatoms is recalled. It has been estimated that a million individuals might come from one in the course of a month. If this is the fact, it is perhaps not strange that large amounts of silicious material accumulated in places where conditions were favorable for diatoms. Volcanic ash is also a constituent of the Lower Miocene. As implied above, the Miocene is generally unconformable on the Eocene or on older formations.

After the early Miocene, igneous eruptions were extensive in eastern Washington, Oregon, and the Coast ranges of California. South of San Francisco, this was the time of the last important eruptions in the Coast ranges, though vulcanism continued later in Oregon and Washington, and perhaps to some extent in northern California. The igneous eruptions accompanied the Mid-Miocene diastrophism referred to above, which consisted in the readjustment of fault-blocks and folds throughout the Pacific coast region. This readjustment went so far that even high mountains were developed locally, as shown by the coarseness of the sediments which followed.

After the diastrophism referred to, the extension of the sea over present lands on the Pacific coast was greater than at any time since the Eocene. It was not until this time that the northern part of the Central valley of California (Sacramento valley) was

¹ Eldridge, Bull. 313, U. S. Geol. Surv.; Arnold and Anderson, Bull. 322, U. S. Geol. Surv.

submerged. The Upper Miocene beds are therefore more widespread than the Lower. While clastic sediments predominate, diatomaceous earths are still in evidence.



Fig. 542.

Fig. 542.—Map showing supposed distribution of land and water on the Pacific coast of the United States during the early Miocene period. (Ralph Arnold.)



Fig. 543.

Fig. 543.—Map showing supposed distribution of land and water on the Pacific coast of the United States during the late Miocene period. (Ralph Arnold.)

The marine part of the Miocene system attains very notable thickness, the Lower Miocene having a maximum thickness of some 8,000 feet (Vaqueros 3,000, Monterey 5,000) and the Upper Miocene hardly less.

By the close of the Miocene, the peneplanation of the Klamath and Sierra Nevada mountains seems to have approached completion. Much of the material eroded from these mountains had been deposited in the central valley of northern California, giving the thick Miocene beds of that valley.

In western Oregon, Miocene (*Empire*) beds a few hundred feet thick, containing volcanic ash, rest unconformably on the deformed

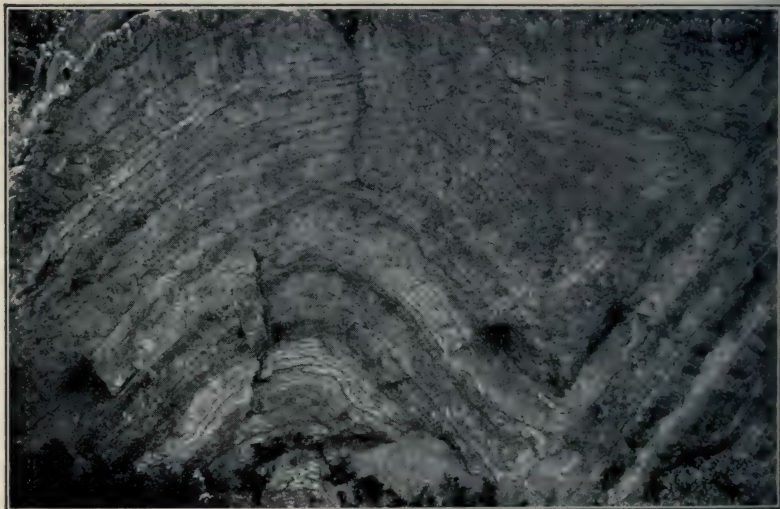


Fig. 544.— Contorted beds of Monterey shale. Mouth of Vaquero Creek, Cal. (Lippincott, U. S. Geol. Surv.)

and eroded Eocene.¹ In British Columbia, there are both elastic and volcanic rocks referred to this period.

The Miocene of the western coast has not the simple structure of the corresponding beds along the Atlantic and Gulf coasts. The strata have been deformed so as to stand at high angles (Fig. 544) in many places, and locally (Mount Diablo range), they have been folded, and the folds overturned so that the Chico (p. 752) and Tejon (p. 781) series overlies the Miocene.² The Miocene beds

¹ Diller, Coos Bay and Port Orford folios, U. S. Geol. Surv.

² Turner, The Geology of Mount Diablo, Bull. Geol. Soc. Am., Vol. 2, 1891.

are found in some parts of the Coast Range¹ of California up to elevations of 2,500 feet.

Non-marine deposits. The sea seems not to have overspread the northern part of the central valley of California when it did the southern, and at the north there were deposits of estuarine, lacustrine, and probably subaërial origin (*Ione* formation) contemporaneous with the marine beds farther south. They consist of the common sorts of elastic sediments, with some coal, iron, etc.

Along the east side of the central valley of California, auriferous gravels,² brought down by streams from the Sierras, were being



Fig. 545.—Section showing the structure and relations of the Miocene system in the San Luis Obispo region of southern California. *Jsl*, San Luis formation, Jurassic; *Nm*, Monterey shale, Miocene; *Nrt*, rhyolite tuff; *Np*, Pismo formation, Miocene (?); *Npr*, Paso Robles formation, Pliocene; *Pal*, recent alluvium, etc.

deposited in the lower courses of the valleys during at least a part of the period. These gravels seem to have been deposited on a surface of slight relief, interpreted as a peneplain.³ The tilting of this plain toward the end of the Miocene seems to have quickened the upper parts of the streams and caused them to deposit gravel below. The Sierra Mountains are thought to have been at least 4,000 feet lower than now when these gravels were deposited. From some of the gravels of California, thought to be of Miocene age, human relics have been reported,⁴ but there seems to be the best of reason for doubting their authenticity.

Non-marine Miocene beds are rather wide-spread in south-

¹ Lawson and Palache, Bull. Dept. Geol., Univ. of Cal., Vols. I and II; Ashley, Jour. Geol., Vol. III, p. 434; and Fairbanks, Jour. Geol., Vol. VI, p. 561.

² Whitney, The Auriferous Gravels of the Sierra Nevada of Calif.; Turner, 14th Ann. Rept., U. S. Geol. Surv., 1894; Lindgren, Jour. Geol., Vol. IV, 1896, pp. 881–906; Diller, Jour. Geol., Vol. II, pp. 32–54. See also folios of the Gold Belt of Calif., U. S. Geol. Surv.

³ Diller, Jour. Geol., Vol. II, pp. 33–54.

⁴ Whitney, op. cit.

eastern California and Oregon, reaching great thicknesses (4,000 feet, King) at some points in the vicinity of the 40th parallel. In

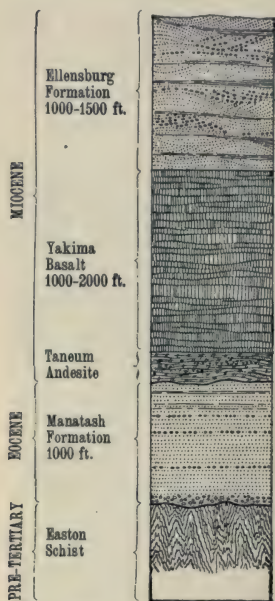


Fig. 546.—Columnar section showing the succession of formations in central Washington. (G. O. Smith, U. S. Geol. Surv.)

general, they are made up of sandstones, conglomerates, volcanic debris, infusorial earths, and fresh-water limestones. Other areas of deposition, some of them lakes, existed during the Miocene in Nevada (*Esmeralda* formation) and Montana (*Bozeman* formation).

Farther east, on the western part of the Great Plains, the deposition of the *White River* beds may have continued for a time after the beginning of the Miocene, as indicated by the fauna of the uppermost beds. Late in the Miocene period, aggradation seems to have been renewed in the same general area, and the *Loup Fork* formation, thin but extensive, was spread out over great areas, from South Dakota to Mexico. The lacustrine phases of this formation are probably less extensive than the subaërial.¹ To the north, the *Loup Fork* beds are often unconformable on the *White River* beds, and like the latter have given rise to "bad land" topography.

Lake and other terrestrial deposits, largely of volcanic material, are known north of the United States, especially in that part of British Columbia² between the Coast and Gold ranges. Miocene deposits are known in Alaska, but erosion rather than deposition was the dominant process there so far as present data show.

Igneous activity during the Miocene. The wide-spread igneous activity which began with the close of the Cretaceous continued, and perhaps reached its climax during the Miocene. Igneous materials abound in the sedimentary formations of the system

¹ Haworth, Univ. Geol. Surv. of Kan., Vol. II, p. 281.

² Dawson, G. M., Trans. Royal Soc. of Canada, 1890.

throughout the west, and igneous activity affected nearly or quite every state west of the Rocky Mountains, and the eruptions were from fissures as well as volcanoes. Among the conspicuous centers of activity the basin of the Columbia¹ and the Yellowstone National Park² may be mentioned. Locally, forests were buried by the volcanic ejecta, and in favorable situations their trunks were petrified (Fig. 548). Great areas of the sedimentary beds of the period are concealed by the lavas, but the extrusions were by no means confined to the areas where sedimentation was in progress. The lavas of at least a considerable part of 200,000 or 300,000



Fig. 547.—Court-House and Jail Rocks. Buttes of the Arikaree (Miocene) formation of western Nebraska. (Darton, U. S. Geol. Surv.)

square miles of lava-covered country in the western part of the United States issued during the Miocene period, or during the time of crustal deformation which brought it to a close.

Volcanoes were active in the Antillean region of Central America and the West Indies, and the Andean system of South America, as well as in North America.

Close of the Miocene. Slow warpings of the surface seem to have been in progress throughout the Cordilleran region during the Miocene period, accompanied by faulting and vulcanism, and

¹ Landes, Wash. Geol. Surv., Vol. II, and Smith, G. O., Ellensburg folio, U. S. Geol. Surv.

² Western folios, U. S. Geol. Surv., notably the Yellowstone National Park folio. Most of the folios showing Neocene formations show volcanic rocks of Neocene age.

locally, by pronounced orogenic movements.¹ But toward the close of the period movements were more general. Pronounced

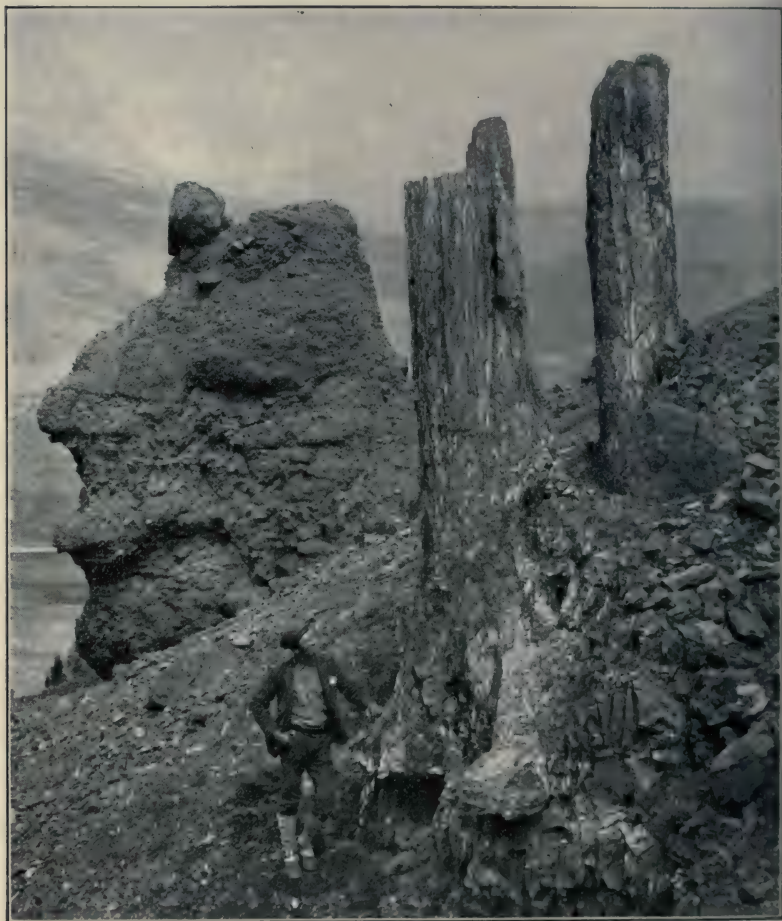


Fig. 548.— Petrified tree-trunks, Yellowstone National Park. (Iddings, U. S. Geol. Surv.)

deformative movements affected the coastal regions of Oregon²

¹ Ashley, Jour. Geol., Vol. III, p. 434; Whitney, Geol. of California, I.

² Diller, 17th Ann. Rept., U. S. Geol. Surv.

and northern California, tilting and folding the Miocene and older formations. The principal folding of the existing Coast Ranges of both these states has been assigned to this time,¹ but it now appears that some of the deformations heretofore referred to the end of the Miocene, took place after the Early Miocene (p. 808). The Cascade Mountains of Washington were in process of growth at this time.²

Similar movements appear to have been wide-spread east of the coast, resulting, in some places, in the deformation of strata heretofore horizontal, but more commonly affecting formations and areas which had suffered deformation at some earlier time. In northern California, the deformation was such as to emphasize the central valley of the state though raising its northern part. Deformation and faulting seem also to have been wide-spread and pronounced in the Great Basin region, and elsewhere.

The later part of the period was perhaps the time when the greater relief features of the rugged west, as they now exist, were initiated. The great relief features of earlier times appear to have lost their greatness before the end of the Miocene (p. 810). After the movements of the late Miocene had been accomplished, it is probable that the western part of the continent had a topography comparable, in its relief, to that of the present, though by no means in correspondence with it. The details, and even many of the larger features, of the present topography are of still later origin. Subsequent changes have been the result of (1) deformation, largely without notable folding, (2) faulting, (3) the extrusion of lava, and (4) extensive degradation and aggradation, by running water, by ice, and by wind.

In the eastern part of the continent, the geographic changes were less considerable, though the Atlantic and Gulf regions seem to have emerged, transferring the coast-line to some such position as it has to-day.

Foreign

Europe. The relations of sea and land remained much as in the early Tertiary, though the area of the sea was somewhat restricted

¹ Ashley, op. cit.

² Willis, Professional Paper 19, U. S. Geol. Surv.

in northern Europe, and extended in the southern part of the continent. Non-marine formations have much representation in this, as in most other post-Paleozoic systems. Some of the non-marine formations are of brackish-water origin, and some of fresh. The marine beds occur chiefly along the Atlantic and Mediterranean coasts. The marine Miocene of Germany, Holland, and Belgium, is largely buried beneath glacial drift, and the exposed parts of the system are chiefly of non-marine origin. They include coal and tuff, besides the commoner clastic sediments. Thick conglomerates (3,900–5,900 feet) of early and Middle Miocene age are found along the north base of the Alps (Rigi), and tell something of the relief of the Alpine region at the time.

From the shallow epicontinental sea which covered parts of Belgium and France, there may have been a sea connection by way of the Garonne, with the Mediterranean along the northern base of the Pyrenees. The strait of Gibraltar is thought to have been closed, and southern Spain joined to Africa; but there were perhaps straits across Spain, as across southern France, connecting the Atlantic with the southern sea.

Southern Europe appears to have been an extensive archipelago, the plateau of Spain, parts of the Pyrenees, the Alps, and the Carpathian Mountains, and portions of adjacent lands, being islands. The sea of southern Europe was expanded eastward far beyond the limits of the present Mediterranean. Late in the period, there was a notable withdrawal of the sea from the land.

The Miocene formations include all the ordinary sorts of sedimentary rocks common to marine and non-marine deposits. The latter include not a little limestone of fresh-water origin, made partly from the secretions of algæ. The system has great development in Italy, where it is said to attain a thickness of nearly 6,000 feet.

In spite of the wide sway of the southern sea of Europe, the Miocene formations do not appear at the surface in great areas, though found in all countries bordering the Mediterranean, both in Europe and Africa. In most of these countries, the lower formations are of marine origin, and the upper of brackish- or fresh-water origin. They occur in Syria, but not in Arabia and Persia,

showing that the earlier connection between the Mediterranean and Indian Ocean regions had come to an end.

Close of the Miocene in Europe. In Europe, as in America, considerable disturbances occurred in the later part of the period, and at its close. Before its end, the Alps had had a period of growth, usually placed at the close of the Lower Miocene. The Apennines and other mountains of southern Europe also were in process of development during the later Miocene. In the Caucasus Mountains, Miocene beds occur up to heights of 2,000 meters. It will be seen, therefore, that deformative movements, involving the great mountain systems of the continent, were in progress in southern Europe during the later part of the Miocene period. As in America, widespread movements which were not notably deformative attended the growth of the mountains, with the result that the sea which had overspread southern Europe was greatly restricted, though not reduced to its present size. Igneous activity appears to have attended the movements of the time, but not on so great a scale as in North America.

Other continents. The Miocene of *Asia* has not been generally separated from the other Tertiary formations, but is known to be widely distributed in the southern part of the continent.¹ In Japan² and some other parts of northeastern Asia, the Tertiary (Miocene?) contains petroleum and metaliferous veins. A rich Miocene fauna, both marine and terrestrial, is found in Java.

In *Africa*, Miocene formations occur in Algeria and in Lower Egypt. *Australia* and New Zealand are rich in Miocene beds, some of which are marine, and some terrestrial. Igneous rocks are associated with the sedimentary. The beds are found up to heights of 4,000 feet, giving some clue to the extent of post-Miocene crustal deformation here.

In *South America*, Miocene beds probably occur in the western coast, and are known to have extensive development on the eastern plains of the southern part of the continent,³ where the distinction between the Upper Oligocene and the Miocene is not sharp. The

¹ Oldham, Geol. of India. ² Geology of Japan, Imp. Geol. Surv., 1902.

³ Hatcher, Sedimentary Rocks of Southern Patagonia, Am. Jour. of Science, Vol. IX, 1900; and Ortman, Princeton Univ. Repts. of Expedition to Patagonia, Vol. IV, Pt. II.

lower part of the Oligocene-Miocene series (*Patagonian* beds) is marine, while the upper part (*Santa Cruz*) is of fresh-water origin. The terrestrial faunas of this region are strikingly similar to the Miocene and later faunas of Australia and New Zealand. This relationship has caused speculation as to an Antarctic continent connecting these regions.

Arctic latitudes and climate. Miocene beds are somewhat widely distributed in the Arctic regions and seem to be largely of terrestrial origin, with the fossil floras indicating a warm temperate climate. Forty-six of the 137 species of plants found in North Greenland ¹ (Lat. 70° and less), including species of sequoia and magnolia, are also found in central Europe, and the floras of Spitzbergen and Grinnell Land were hardly less luxuriant.

Curiously enough the Miocene plants of Alaska, Kamschatka, and Japan indicate a climate cooler than that of the higher latitudes. It seems probable that this apparent discrepancy is the result of imperfect correlation, the fossils indicating these inharmonious conditions not being contemporaneous. The fauna of New Zealand is distinguished by the great size of some of its molluscan shells. Both the flora and fauna have a tropical aspect, the fruit of the palm having been found as far south as latitude 45°.

THE LIFE OF THE MIOCENE

The Land Plants

The mid-latitude flora of the Miocene records the gradual disappearance of subtropical types, and an increase of deciduous trees. This is particularly true of North America, where the flora came to resemble that of to-day in somewhat lower latitudes, and is indeed its predecessor. An important feature in North America was an increase in the grasses, with its appropriate effect on mammals.

How far the gradual removal to the south of the forms now regarded as tropical or subtropical, and how far the concentration at the north of the forms that now characterize those latitudes were the result of a natural segregation of the previously mingled forms, and how far the result of changes of climate, it is perhaps unsafe to say; it has usually been attributed to the latter.

¹ Heer, *Flora Fossilis Arctica*, 1868-83, and Q. J. G. S., 1878. There is some question as to the Miocene age of these fossils.

The Land Animals

The earlier fauna. The early Miocene (John Day epoch¹) land fauna of North America was very distinct from the late Miocene (Loup Fork epoch). The earlier resembled the Oligocene (White River) fauna in general aspect, but most of the mammalian genera and nearly all the species were new and more modern. Primitive carnivores were succeeded by true carnivores, chiefly of the cat and

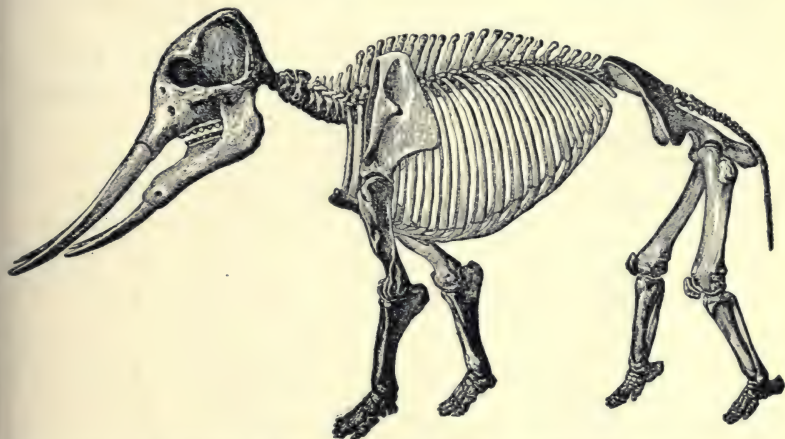


Fig. 549.— A Miocene Mastodon, *Tetrabelodon angustidens* Cuvier. (Restoration by Gaudry.)

dog families. Several branches of the perissodactyls had disappeared, reducing them essentially to their three persistent lines, exemplified by the horse, the tapir, and the lowland rhinoceros. The even-toed branch also had developed into modern lines. Rodents were abundant, including squirrels, beavers, gophers, rabbits, etc.

The later fauna. Elephants. A notable addition to the mammalian fauna of North America in the late Miocene, was the proboscideans. Primitive proboscideans lived in Egypt at least as early as the Middle Eocene, and in Europe in the early Miocene. Elephants reached North America in the late Miocene, and South America in the Pliocene.

¹ Perhaps all the John Day beds should be classed as Oligocene (p. 781).

Ruminants. Much more important was the immigration of the modern ruminants. Certain branches of the ruminants had been represented previously, but the great ruminant group that later formed so important a part of the fauna does not seem to have descended from the early North American forms, but to have immigrated from Eurasia. They are first recorded in the Loup Fork beds. The first immigrants belonged to the deer and ox families. The earliest known deer (excluding *Protoceras*) were from Europe. They were hornless, as are their surviving relatives in Asia. By the middle of the Miocene, some of the males had acquired small two-pronged deciduous antlers, fixed on long bone pedicles. About the close of the period, three or four prongs were added, and in the Pliocene the antlers were variously branched and the pedicles shortened to insignificance, as in most living deer. This historical evolution of the antlers is reproduced in the individual history of the modern male deer. Born hornless, he acquires in successive years the single, the bifurcate, and the more and more complexly branched antlers that mark the history of the race. It was in the bifurcating stage that the deer appeared in America, its antlers being simple and small, but variable. The skeletons imply lightness and speed, but not to the same degree as later.

There is some doubt as to the precise stage to which the remains of bison found in Nebraska and Kansas are to be assigned. They have usually been referred to the Lower Pliocene; but Matthew assigns them to the Upper Miocene, and Williston to the early Pleistocene.¹ The earliest known bisons on the Eurasian continent have been found in the Siwalik formation of India, which is regarded as Lower Pliocene.

The more primitive genera of camels had disappeared, but 15 species of more modern type have been identified from the Loup Fork formation. The family seems to have been confined still to North America.

The evolution of the horse. The Miocene was a great epoch in the evolution of the horse; *Anchippus*, *Protohippus*, *Pliohippus* (*Merychippus*), *Hipparion*, and other genera flourished and deployed into forty or more species. They were still three-toed, but

¹ Bull. Am. Mus. Nat. Hist., XII, 1899, p. 74.

the two lateral toes were dwarfed and did not usually touch the ground, while the central one was strengthened and bore all the weight. A large group of structural features were being modified concurrently with the feet, to fit the evolving horse to dry plains and grassy food (Fig. 551). The elimination of the side toes, the lengthening of the limbs, the change of the joints to the "pulley-wheel" type, the concentration of the limb muscles near the body to reduce the weight of the parts most moved, and the consolidation

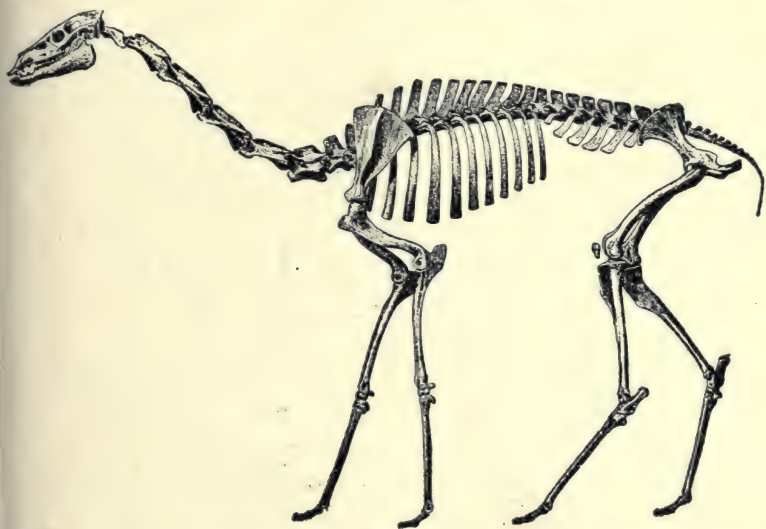
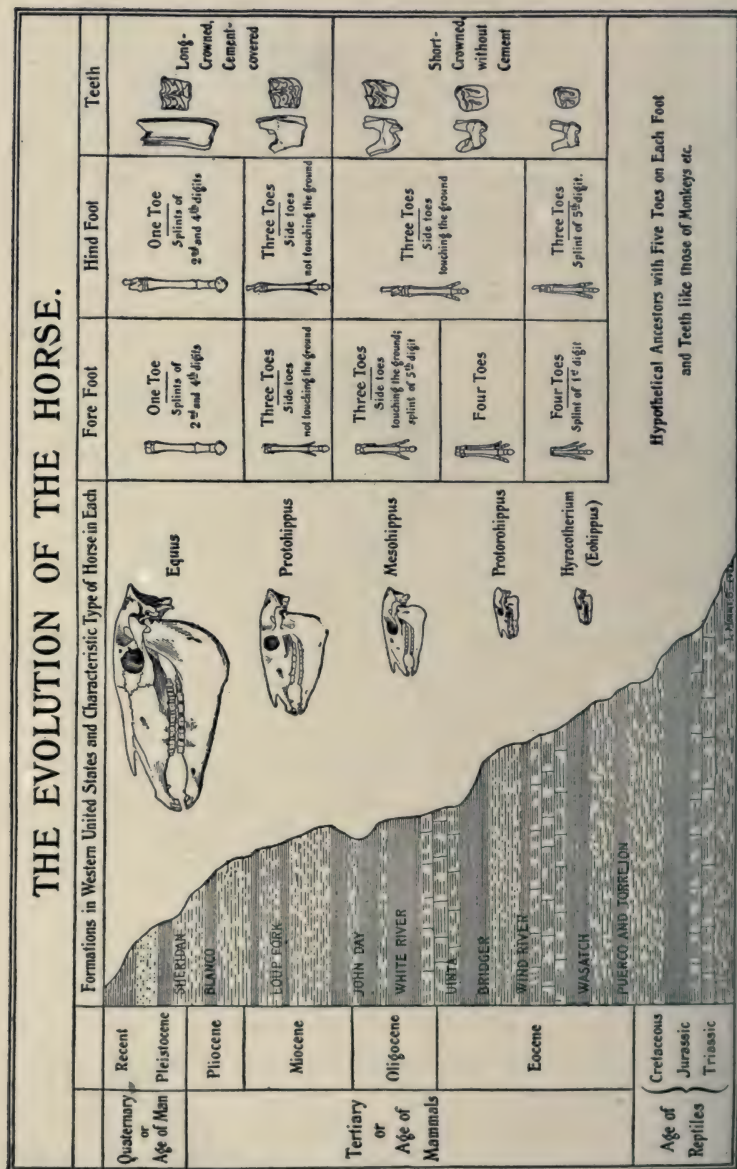


Fig. 550.—An American Miocene Camel, *Oxydactylus longipes* Peterson, from the Loup Fork beds of Nebraska. (Peterson.)

of the leg bones, were modifications in the interest of speed and strength. An elongation of head and neck was necessary to reach the ground. The front teeth were reduced to chisel-like, cropping forms, somewhat resembling those of the rodents, while the molars evolved a tortuous distribution of the enamel so flanked by dentine and cement that the differences of wear gave rise to ridges of enamel suited to grinding, and protected against breaking by supporting dentine and cement on either side. The teeth were also gradually elongated to provide for the great wear caused by the

THE EVOLUTION OF THE HORSE.



Hypothetical Ancestors with Five Toes on Each Foot
and Teeth like those of Monkeys etc.

Fig. 551.— The evolution of the horse. (After William D. Matthews, Am. Mus. Jour.)

dry silicious grasses.¹ It is probably as safe to infer a development of dry, grassy plains from this evolution of the horse, as to infer climatic and topographic conditions from plants and other organic adaptations.

Tapirs and rhinoceroses. Tapirs were but meagerly represented, but rhinoceroses, though the running and swimming branches had disappeared, were prominent. The American species were still mainly hornless (*Aceratherium*), though slight indications of horns appeared in one genus (*Diceratherium*). Two-horned species appeared during the period in Europe.

Carnivores. The carnivores were abundant, and had assumed forms referred with some doubt to the living genera *Canis*, *Felis*, *Mustela*, and *Putorius*. The dog family embraced numerous wolves and foxes; the cat family, panther-like animals and saber-toothed cats; the *Mustelidæ*, weasel-like and otter-like forms, and an ancestral coon. The genera of the Loup Fork epoch were nearly all different from those of the John Day epoch, indicating rapid evolution. Other existing families of carnivores lived in Europe.

Other orders. Rodents were abundant, but neither insectivores nor primates are among the North American fossils. The development of the plains which favored horses, deer, and cattle, was obviously unfavorable to the lemuroids.

Primates. In the Old World, true apes had appeared. One type was a rather large annectant form, combining some of the characters of apes and monkeys; another was a generalized type related to the chimpanzee and gorilla, and about as large as the former. It is the view of some paleontologists that the ancestral branch of the *Hominidæ* must have diverged from its relatives at least as early as this; but on the origin of the *Hominidæ*, the record throws no direct light.

The lower vertebrates. Little of moment is recorded relative to the lower vertebrates. Not much is known of American Miocene birds, but their advancement in later stages implies that they continued their evolution with measurable rapidity, a conclusion sup-

¹ An excellent recent statement of the evolution of the horse, admirably illustrated, is given by Matthew, Sup. to Am. Mus. Jour., Vol. III, No. 1, Jan., 1903.

ported by the European evidence. Reptiles had very generally assumed modern forms, and were represented by turtles, snakes, and crocodiles. Amphibians came again to notice in the form of a large salamander, whose remains, found at Oeningen, Switzerland, formerly attained an unworthy celebrity from false identification as a human skeleton, and from the application of the pretentious name *Homo diluvii testis*.

Summary. A general view of the American Miocene land fauna shows that the great order of ungulates took precedence in evolution, and that both the odd- and even-toed branches participated actively. Closely following these in importance, and dependent on them for the conditions of their evolution, came the carnivores. Rodents occupied a middle position, and insectivores and lemuroids declined notably.

The European record bears a similar general interpretation, with the ungulates somewhat less pronouncedly in the lead, the carnivores somewhat better deployed, and the proboscideans a conspicuous factor. The important evolution of the higher primates seems to have been confined to the Old World.

The Marine Life

Provincialism dominant. The pronounced provincialism that had been inaugurated in the Oligocene epoch continued throughout the remainder of the Cenozoic era. There was some amelioration during the Miocene, but it was not marked. No essential relief was possible so long as the shallow seas remained mere bordering tracts, as in North America, or mere bays and straits, as in Europe. Even the narrow border tracts that were geographically continuous show signs of having been cut into biological sections by interrupting barriers. Such barriers had perhaps been operative in certain earlier periods, but their influence there is not so well recorded. The land area being large, large rivers reached the coast here and there, and poured great volumes of fresh and muddy waters across the shore belt, doubtless forming barriers to some species, though probably not to all. The warpings of the crust probably projected peninsulas and submarine ridges out upon and perhaps across the continental shelf. These were not only barriers in themselves, but

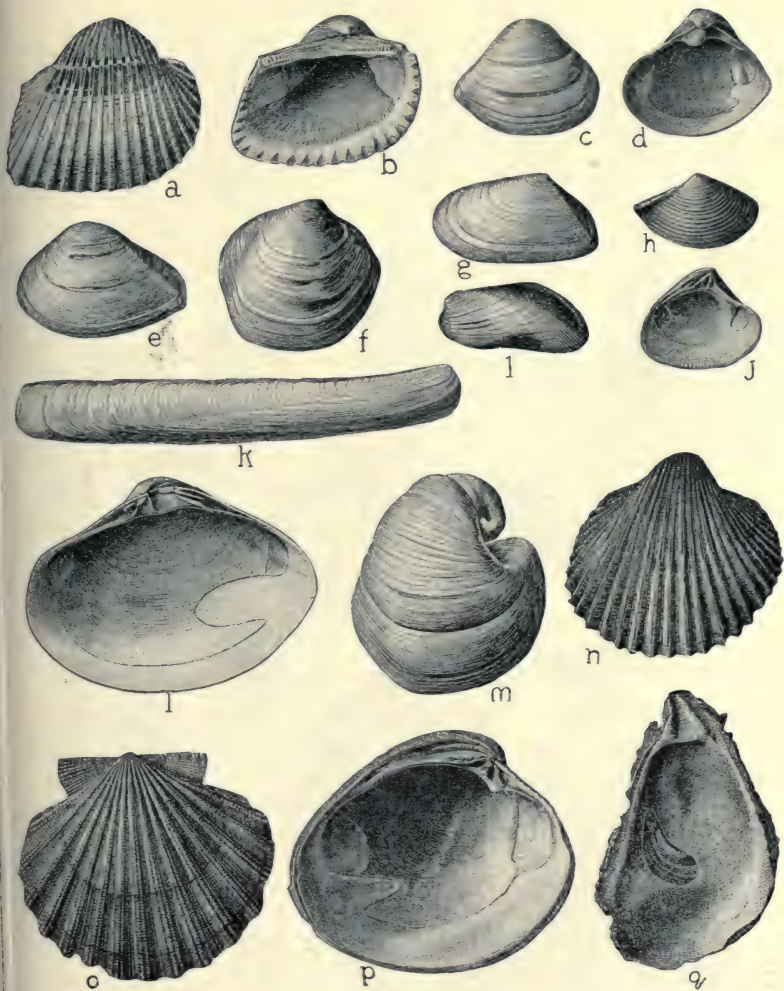


Fig. 552.—MIOCENE PELECYPODS: *a* and *b*, *Arca* (*Scapharca*) *staminea* Say; *c* and *d*, *Corbula idonea* Conrad; *e*, *Crassatellites marylandicus* (Conrad); *f*, *Phacoides* (*Pseudomiltha*) *foremani* (Conrad); *g*, *Tellina* (*Angulus*) *producta* Conrad; *h*, *Leda concentrica* (Say); *i*, *Modiolus dalli* Glenn; *j*, *Astarte thomasi* Conrad; *k*, *Ensis directus* (Conrad); *l*, *Spisula* (*Hemimactra*) *marylandica* Dall; *m*, *Isocardia markoëi* Conrad; *n*, *Cardium* (*Cerastoderma*) *leptopleurum* Conrad; *o*, *Pecten* (*Chlamys*) *madi-sonius* Say; *p*, *Venus ducatelli* Conrad; *q*, *Ostrea carolinensis* Conrad. (Maryland Geol. Surv.)



Fig. 553.—MIOCENE GASTROPODS (one Scaphopod): a, *Turritella variabilis* Conrad; b, *Scala sayana* Dall; c, *Nassa marylandica* Martin; d, *Terebra unilineata* Conrad; e, *Solarium trilineatum* Conrad; f, *Cancellaria alternata* Conrad; g, *Surcula biscatenaria* Conrad; h, *Calliostoma philanthropus* (Conrad); i, *Actæon shilohensis* Whitfield; j, *Oliva litterata* Lamarck; k, *Retusa* (*Cylichnina*) *conulus* (Deshayes); l, *Conus diluvianus* Green; m, *Polynices* (*Neverita*) *duplicatus* (Say); n, *Fis-*
(Continued at bottom of page 827.)

had an influence in directing the courses of the coast currents. Differences of climate in different latitudes had been developed apparently, and cold and warm currents were probably more pronounced than in earlier times, and their shiftings had still graver effects upon the faunas. So too, the lower temperatures in the northern shore tracts of the Atlantic and Pacific prevented their serving longer as migratory routes for warm-water species, and this tended further to intensify the provincial nature of the shallow-water faunas.

According to Dall, the Chesapeake Miocene was ushered in by a marked faunal change due to a cold northern current driving out or destroying the previous warm-water fauna of the region, and bringing with it a cold-water fauna. There was a complete change of species, and even some genera were displaced. The fauna retained, however, a general molluscan aspect. Both the bivalves and the univalves gave proof of better adaptability to the vicissitudes of the coastal tracts than most other forms, and whether warm or cold waters prevailed, held their dominance. Figs. 552 and 553 show a few of the characteristic types. Compared with the Eocene group, Fig. 535, the resemblances will be found more striking than the differences.

Notwithstanding the provincializing agencies, there were many close correspondences between the faunas of the western and the eastern sides of the Atlantic,¹ probably due partly to intermigration and partly to parallel evolution.

The marine fauna of the Pacific coast indicates a climate but little warmer than that of the present, and this conclusion is reinforced by the plants of the Puget Sound region, which record transition from the subtropical climate of the Eocene to the temperate climate of the present. The fauna of the Upper Miocene indicates a still closer approach to the present.²

¹ Md. Geol. Surv., Miocene volume, 1904, pp. 151-153.

² Arnold, Ralph, Jour. Geol., Vol. XVII. For Miocene marine fossils of the Pacific coast, see Dall, Professional paper 59, U. S. Geol. Surv.

suridea alticosta (Conrad); *o*, *F. griscomi* (Conrad); *p*, *Xenophora conchyliophora* (Born); *q*, *Crepidula fornicata* (Linné); *r*, *Fulgar spiniger* (Conrad) var.; *s*, *Ecphora quadricostata* (Say); *t*, *Siphonalia marylandica* Martin; *u*, *Ilyanassa* (?) (*Paranassa*) *porcina* (Say). *Scaphopod*: *v*, *Dentalium attenuatum* Say. (Maryland Geol. Surv.)

CHAPTER XXIX

THE PLIOCENE PERIOD

The most distinguishing feature of the Pliocene, so far as the present continents are concerned, is the predominance of terrestrial deposits. This is a consequence (1) of the exceptional deformations which took place during the period, and just before its beginning, and (2) of the recency of the period, which has saved its deposits, to a large extent, from removal. Similar deposits in similar amounts during and after other periods of comparable deformation, have been largely removed by subsequent erosion. These deposits of the Pliocene are perhaps most obvious in intermontane regions such as the Great Basin. They have sometimes been interpreted as lacustrine deposits, and such deposits no doubt exist; but over areas much greater than those occupied by lakes in Pliocene times, and over tracts which never formed parts of well-defined flood plains, broad aprons of detritus accumulated. Such accumulations are now most considerable at bases of mountains whose steep slopes join plains of low gradient, and where the climate is sub-arid, the rain falling in sudden and copious showers, largely concentrated on the mountain heights. The thirsty plains below, covered with porous debris, quickly drink up the descending floods and strand the detritus they bring down. Most of the western mountains of America are flanked by such deposits, some of which are of Pliocene age, and some younger. In lake basins, subaërial sediments merge into lacustrine, and the two may be interstratified. The deposits in question merge so insensibly into flood-plain deposits that they cannot be separated from them in all cases; nor should they be, since they are of the same essential nature. Pliocene deposits of this type are doubtless concealed beneath later accumulations of a similar sort in nearly all the large basins, and at the bases of nearly all the steep slopes in the western mountain region.

East of the Rocky Mountains, on the western border of the plains, deposits of this class are wide-spread. Some of them are Pleistocene, and some are probably older. In many places these gravels show by their constitution that they came from the mountains, and in some situations they have been shifted repeatedly (p. 181), always farther from the mountains and to lower levels (Fig. 555), with the result that they now constitute a series of deposits of somewhat different ages, rather than a single formation assignable to a definite epoch.

In the Mississippi basin, far from all mountains, there are patches of gravel on various hills and ridges, which are interpreted as the remnants of a once more or less continuous mantle of river detritus. The definite correlation of these gravels is not now possible, and they may not all be of the same age. They are not older than Cretaceous, and are older than the glacial drift. Their similarity to the Lafayette (Pliocene) gravels farther south suggests their correlation with that formation. The material of these gravels, almost wholly quartz, quartzite, and chert, is partly local, and partly from the north. The leading topographic features of the Mississippi basin have been developed since their deposition, for their remnants are on the crests of the highest lands within the area where they occur.

About the Atlantic and Gulf coasts similar deposition gave rise to the *Lafayette* (Orange Sand) formation. This formation has been so variously interpreted that it merits special consideration, and the interpretation here given it is not unchallenged.

*The Lafayette Formation*¹

This formation has an extensive distribution, (1) between the Piedmont plateau and the Atlantic, (2) on the inland part of the Coastal Plain of the Gulf of Mexico, and (3) in the southern part of

¹ The fullest sketch of this formation as a whole is that of McGee in the Twelfth Annual Report of the U. S. Geological Survey. A few references to other accounts of the formation in special localities, often under other names, are as follows: Safford, *Am. Jour. Sci.*, Vol. XXXVII, 1864; Hilgard, *Agric. and Geol. of Miss.*, 1860, and *Am. Jour. Sci.*, Vol. XLI, 1866, and Vol. IV, 1872; Salisbury, *Geol. Surv. of Ark.*, Report on Crowley's Ridge, 1889; Dumble, *Jour. Geol.*, Vol., II, 1894, p. 560; Smith, E. A., and Johnson, L. C., *Geol. Surv. of Ala.*, 1894.

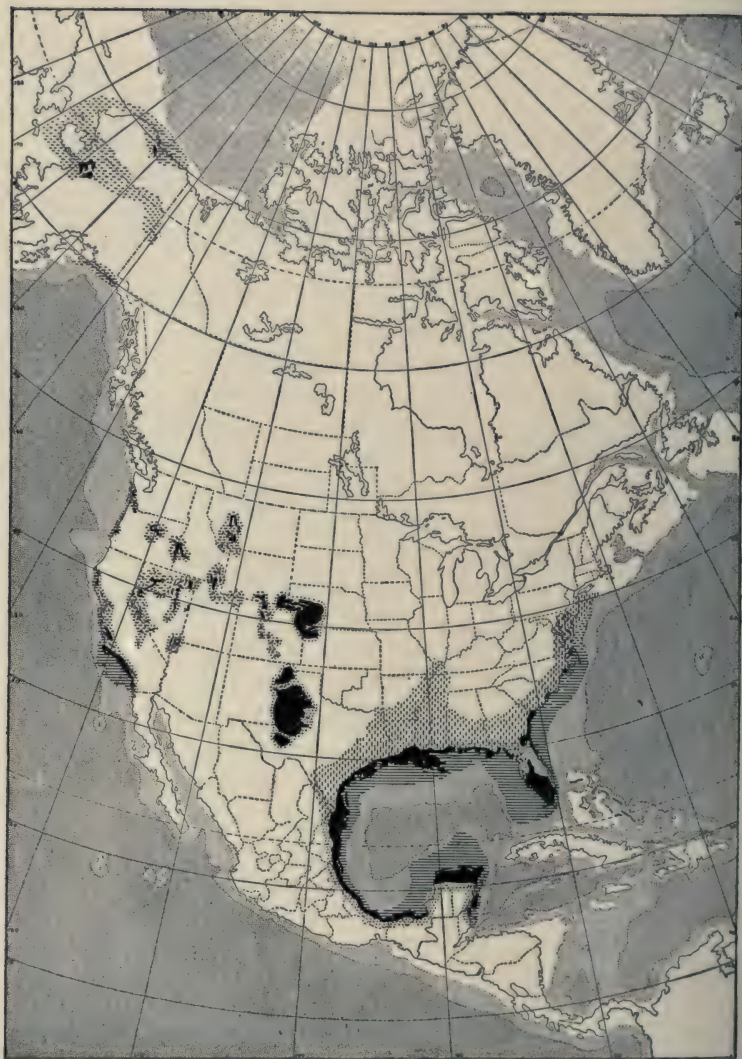


Fig. 554.— Map showing the distribution of the better-known parts of the Pliocene system. The area of the Lafayette, along the Atlantic and Gulf coasts, is marked by vertical dashes. This formation is doubtless more wide-spread than the map shows, as indicated in the text. Relatively little of the exposed Pliocene is marine.

the Mississippi basin, and is represented, if our interpretation is correct, (4) in the valleys west of the Appalachians. On the Coastal Plain of Texas, the formation is connected with analogous deposits on the Great Plains, and through them with the intermontane deposits of the west, already mentioned. The term Lafayette has been usually applied only to the formation on the slope between the Appalachians and the Atlantic, about the Gulf, and in the Mississippi basin below the Ohio. Thus limited, the formation has been estimated to have an area of some 250,000 square miles. It lies upon the eroded edges of all older formations of the region, from pre-Cambrian to Miocene. It extends inland from the coast up to altitudes of 1,000 feet¹ near the Rio Grande, 800 feet in Tennessee, and 300 to 500 feet on the Atlantic slope.

At its mountain-ward edge, ragged belts of the Lafayette formation follow the valleys up into the mountains, and unless our identifications are in error, they reach back with local interruptions, into the intermontane valleys. At its seaward margin, it is more or less completely concealed by younger beds, and it is not to be doubted that it passes out to sea beneath them. No part of the formation now known on land is demonstrably marine.

It is not to be understood that the Lafayette formation occurs everywhere within the general area of its distribution. Over considerable areas, it caps divides, but is absent from the valleys between them, obviously the result of stream erosion. The base on which the formation rests has but little relief, and a gentle dip seaward. It appears to have been either in an advanced stage of erosion when the Lafayette formation was deposited, or too low to have become notably rough as a result of erosion.

Thickness. In general, the formation thickens seaward; but at any given distance from the sea, it is thicker in the valleys which affected the surface on which it was deposited, and thinner on the divides between them. The known thickness ranges from 0 to 200 feet or more. Sections of 20 or 30 feet are common, and of more than 50 feet are rare.

Constitution. The Lafayette is composed of gravel (and occasionally boulders), sand, silt, and clay, variously related to one

¹ McGee, loc. cit.

another. It may be said to be both heterogeneous and homogeneous; that is, there is considerable variation in composition in short distances, and but little more in great ones. In the lower Mississippi valley, whence the name is derived (Lafayette County, Miss.) it is of sand and gravel chiefly, the coarser phases being along drainage lines where it has the distinctive characteristics of fluvial sand and gravel. Over a broad tract of the uplands east of the Mississippi and away from valleys generally, it is composed largely of silt and clay. Its constituents are largely the insoluble residues of older formations farther up the slope on which the formation lies, chert and quartz pebbles making up the gravels, and other insoluble matter the fine constituents.¹ These constituents replace one another at short intervals and in various ways, and no systematic succession is observable. Lens-like masses are not uncommon. Irregular stratification is the rule, but some portions are not bedded or laminated. Certain lenses of sand suggest an eolian origin. A singular pebble-earth that finds its analogue in subaërial and flood-plain deposits is common.

The color of the formation ranges from brick-red through various pinks, purples, oranges, and yellows, to white. The color is more irregular than the composition, bands, blotches, and mottlings diversifying the structural units.

Fossils. Fossils are rare. In its unquestioned and representative parts they are all of land plants and animals (except, of course, the fossils derived from earlier formations). The formation is so much dissected that it is well exposed to observation, and the rareness of known fossils is not due to lack of adequate search.

Origin. The preferred interpretation of the Lafayette formation is as follows: After the base-leveling of the region before the Comanchean period,² the Appalachian tract was bowed up and a new stage of degradation inaugurated. During the earlier part of the Tertiary, a partial peneplaning of the less resistant tracts was accomplished, accompanied by relative subsidence along shore.

¹ Hilgard, *Am. Jour. Sci.*, Vol. IV, p. 266, 1872.

² Rivers of Pennsylvania, and Geographic Development of Northern New Jersey, *Nat. Geo. Mag.*, Vol. I and Vol. II, respectively. Hayes, chapter on the southern Appalachians, in *Physiography of the United States*.

At the opening of the Pliocene, the Appalachian tract is supposed to have been affected by broad, flat, intermontane valleys, mantled by a deep residual soil and subsoil. The Piedmont tract to the east is supposed to have been a peneplain near sea-level. It is assumed that the upward bowing was felt first in a relatively narrow belt along the axis of the mountain system, that the rise was gradual, and that the rising arch increased in width as time advanced. The first up-bowing rejuvenated the head waters of the streams from the mountain tract, and the surface, with its heavy mantle of residual earth, readily furnished load to the streams. When the streams reached that portion of the peneplain not yet affected, or less affected, by the bowing, they dropped

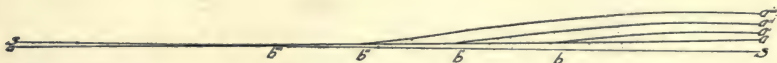


Fig. 555.—Illustrating the progressive stages of arching described in the text, and the attendant shifting zones of deposition; *s-s*, sea-level; *a*, original peneplaned surface with graded slope to sea-coast; *a'*, *a''*, *a'''*, successive stages of arching; *b*, *b'*, *b''*, *b'''*, successive sites of deposition corresponding to stages of arching *a'*, *a''*, *a'''*. In the stage of arching represented by *a''*, the right hand portion of the previous site of deposition is lifted and becomes a part of the area of erosion. The same process is carried farther in the next stage represented by *a'''*.

part of their load (Fig. 555). With continued rise, the zone of deposition is supposed to have been shifted seaward, and the deposits already made were eroded and this material redeposited farther from the mountains and nearer the sea. Thus the process is presumed to have continued till the border of the upraised tract passed beyond the present sea-coast; after which the whole deposit within the area of the present land was subject to erosion, which had reached a notable degree of advancement before the first known glacio-fluvial deposits were laid down. A similar erosion of deposits already made, with redeposition of the materials nearer sea, would have taken place without the seaward widening of the up-arched tract. Fig. 149 shows the sequence of erosion and deposition in this latter case.

The preceding hypothesis of the Lafayette formation postulates that aggradation in each depositional zone developed a plexus of

drainage lines competent to fill the shallow valleys and spread rather generally over the low divides of the coastal peneplain. In the region of deeper valleys, such as the Tennessee, the valleys were only partially filled. It has generally been assumed that the formation was once continuous east of the mountains where patches only now remain; but it may be that the higher divides, especially toward the source of supply of the sediment, were never covered by the formation.

The removal and re-deposition of material in the manner sketched above is regarded as an important part of the interpretation of the formation, and the source of grave difficulty in the correlation of it and its derivatives. The erosion and re-deposition of the material did not cease with the Lafayette epoch, but has been in progress ever since, and the derivatives so closely resemble the parent formation in structure and material that their interpretation is exceptionally difficult.

If it shall ultimately be shown that the seaward portions of the Lafayette, now concealed or unstudied, are marine, the preceding hypothesis would need to be modified only by supposing that as the feeding ground of the streams was bowed up, the coastal border of the plain was submerged. In this case, there should have been estuarine formations in the seaward valleys.

The chief alternative view relative to the origin of this formation regards it as marine¹, deposited during a stage of submergence essentially co-extensive with the area of the formation. This hypothesis has been faithfully applied by geologists of wide familiarity with the phenomena, and abandoned as untenable even where the conditions seem most to favor it. It is, however, still entertained by others. The difficulties felt by those who have abandoned it are (1) the absence of marine fossils; (2) the presence of structural features not indicative of typical marine deposits; (3) the chemical condition, particularly the high and very varying oxidation, and the meager hydration; (4) the topographic relations of the formations, especially the lack of any approach to horizontality of its upper limit; and (5) the absence of shore phenomena. The terraces and cliffs that have been appealed to in this connection,

¹ McGee, 12th Ann. Rept., U. S. Geol. Surv.

are local, doubtfully consistent with one another, and better explained in some other way than by the operation of waves.

Marine Pliocene Beds

The Atlantic coast. If fossils be the test, Pliocene beds of marine origin have little development on the eastern side of the continent. In Florida only (Caloosahatchie beds)¹ have beds containing marine fossils any considerable extent at the surface, though small patches are known farther north.² They may be parts of a continuous formation, chiefly concealed. The time relations of these marine Pliocene beds to the Lafayette are undetermined. Pliocene beds of marine origin have not been certainly identified between Florida and Texas, but they cover considerable areas farther south, as in Yucatan.

The Pacific coast.³ Sedimentation was in progress over less extensive areas along this coast than during the Miocene period. The area of marine deposition especially was greatly restricted (Fig. 556. Compare Fig. 543). The marine deposits are chiefly of fine clastic sediments, while the non-marine deposits contain more coarse material. The maximum known thickness of the marine Pliocene is found south of San Francisco, where about 4,000 feet of strata (*Merced* series) are exposed.⁴ The non-marine part of the system (*Paso Robles* formation) is about three-fourths as thick in the San Joaquin valley.

*Crustal Movements of the Pliocene*⁵

The tendency to crustal movements, both warping and faulting, which had characterized the western part of the continent since the close of the Mesozoic, seems to have continued at least inter-

¹ Dall, Am. Jour. Sci., Vol. XXXIV, 1887, p. 161, Wagner Free Inst. of Science, Vol. XIV, pt. VI, p. 1604, Bull. 74, U. S. Geol. Surv.

² Dall, Trans. Wagner Free Inst. of Sci., Vol. III, Pt. II, pp. 201-217, 1892.

³ Arnold, Ralph, Jour. Geol., Vol. XVII.

⁴ Lawson, Science, Vol. XV, 1902, p. 410, and Hershey, Am. Geol., XXIX, p. 359, give the Pliocene of California greater thicknesses.

⁵ LeConte, Am. Jour. Sci., Vol. XXXII, p. 167, 1886, Bull. Geol. Soc. Am., Vol. II, p. 329, Jour. Geol., Vol. VII, p. 546, 1899; Hershey, Science, Vol. III, p. 620, 1896; McGee, 12th Ann. Rept., U. S. Geol. Surv., and Science, Vol. III, p. 796; also King, op. cit., and Dutton, Mono. I, U. S. Geol. Surv.

mittently through the Pliocene, though the movements which took place during the period are not always distinguishable from those of earlier and later times. Deforming movements often extend through long periods, and the Pliocene movements were in many places probably no more than continuations of those begun earlier.



Fig. 556.—Map showing supposed distribution of land and water on the Pacific coast of the United States during the Pliocene period. (Ralph Arnold).

About the close of the period, movements were extensive and great, resulting in increased height of land. The interval of active erosion which followed is sometimes known as the Ozarkian or Sierran epoch.¹ The region covered by the Lafayette formation was somewhat higher than now, and in reaching this position, was perhaps somewhat deformed. The coast line was probably farther east than now, perhaps at the edge of the continental shelf, across which streams may have flowed. To this epoch, the submerged continuations of the St. Lawrence, the Hudson, the Delaware, the Susquehanna, and the Mississippi are commonly referred. Some of these submerged valleys have great depth, and it has been

assumed that their depth was a measure of the elevation of the land when they were excavated. But if the considerations set forth in Chapter XXXI have force, it is not necessary to postulate such extraordinary changes of level by uplift and depression. Conti-

¹ Hershey, *Science*, Vol. III, p. 620, 1896, and LeConte, *Jour. Geol.*, Vol. VII, p. 529.

mental creep along the slope between the continental platforms and the ocean basins may have lowered the valleys notably as it carried them seaward. The earlier assumption that the land along the Atlantic seaboard must have stood 2,000 to 3,000 feet, or perhaps even 7,000 to 12,000 feet¹ above its present level to allow the excavation of these valleys, may be quite unnecessary, even if the valleys in question are merely submerged river valleys. (See p. 294, and Chapter XXXI).

In the Mississippi basin there was also notable elevation at this time, though probably less than has sometimes been estimated. It seems possible, or perhaps even probable, that the evolution of the principal physiographic features of the interior, so far as due to erosion, began with the Ozarkian epoch, though the study of the evolution of the topography of this region has not advanced so far as to make this conclusion certain.

In the west, too, there were notable closing-Tertiary movements. The plateau region was in process of uplift, periodically, throughout the Tertiary, during which it has been estimated to have undergone an elevation of 20,000 feet (Dutton), and a degradation of 12,000, leaving it 8,000 feet above sea-level. How much of this is assignable to the Sierran epoch is uncertain. It was Dutton's view that the Colorado plateau was so elevated at this time as to rejuvenate the Colorado River, and that the cutting of its inner gorge some 3,000 feet (maximum) below the outer (p. 137), was the work of later times. More recent studies indicate that even the outer and broader part of the valley is younger than was formerly thought, perhaps post-Sierran, and raise a question as to whether the inner gorge is not the result of rock structure, rather than of a distinct and later uplift.² If the whole of the canyon is post-Sierran, the elevation of the region in the Sierran epoch (and later) must have been several thousand feet. The later elevations, largely by blocks, were so recent that the fault scarps are almost always distinct, and independent of stratigraphy and drainage.³

¹ LeConte, *op. cit.*, and Spencer, *Am. Jour. Sci.*, Vol. XIX, 1905.

² Huntington and Goldthwaite, *Bull. Mus. Comp. Zool. Geol. Ser.*, Vol. VI, p. 252; and Davis, *ibid.*, Vol. XXXVIII.

³ Huntington and Goldthwaite, *op. cit.*, p. 248.

In the basin region, faulting and deformation¹ gave rise to depressions between the Sierra Nevada and the Wasatch Mountains, preparing the way for two great Pleistocene lakes (Bonneville and Lahontan). It is probable that many other faults between the Rockies and Sierras were developed at the same time, and in many cases the movement seems to have been along fault planes established earlier.

In the Sierra region, the post-Tertiary (or late Tertiary?) uplift was still more marked.² Not only the deep canyons of these mountains, but all the scenery of the high Sierras is post-Tertiary. "Its bold, rugged, savage grandeur is due to its extreme recency. The wildness of youth has not been tempered and mellowed by age."³ The beginning of the re-elevation of the Sierras, after peneplanation, is usually placed in late Miocene time.

Still nearer the Pacific, notable changes marked the transition to the Pleistocene. In some parts of southern California (Los Angeles County) marine Pliocene beds are said to occur up to altitudes of 6,000 feet,⁴ and in others (San Luis Obispo), there was folding (Fig. 545) and faulting, while the shore-line was pushed out toward the edge of the continental shelf.⁵ There are submerged valleys⁶ along the Pacific coast, as along the Atlantic, but their excavation, instead of following the Ozarkian uplift, has been referred to a somewhat earlier time. Some of these valleys differ from those of the Atlantic coast, in not being the continuations of existing land valleys. The late Pliocene movements and lava flows, the latter filling many of the valleys, are thought to have so disturbed the drainage that the streams no longer reached the sea by their former courses.

In Washington, present knowledge points to the early Pliocene as a time of prolonged erosion. The crests of the Cascade Mountains seem to represent remnants of a deformed peneplain, which, carried to the east and south, is continuous with an erosion plain

¹ King, U. S. Geol. Expl. of the 40th Parallel, Vol. I, p. 542.

² LeConte, *op. cit.*, and Diller, 14th Ann. Rept., U. S. Geol. Surv.

³ LeConte, Jour. Geol., Vol. VII, pp. 529-530.

⁴ Hershey, Am. Geol., Vol. XXIX, p. 364.

⁵ Fairbanks, San Luis folio, U. S. Geol. Surv.

⁶ LeConte, Bull. Geol. Soc. of Am., Vol. II, p. 325.

which cuts across strata (Ellensburg formation) of late Miocene¹ age. The planation must, therefore, have been later than that part of the Miocene period represented by the Ellensburg formation. At least the early part of the Pliocene period, if not most of it, would seem to have been necessary for the accomplishment of this great planation, so that the peneplain can hardly be thought to antedate late Pliocene time. If this is correct, the main features of the present topography of this rugged region are the result primarily of Pleistocene erosion on the peneplain uplifted and deformed in, or subsequent to, late Pliocene time, and secondarily of vulcanism, which has built up the great volcanic piles (Rainier) and others) which affect the region. In British Columbia also, the Pliocene is thought to have been primarily a time of erosion.

Deformative movements of the orogenic type seem not to have been common at the close of the Pliocene, but such movements affected the Santa Cruz Mountains of California, where Miocene (Monterey) and Pliocene (Merced) beds were deformed together.²

On the whole, the close of the Pliocene must be looked upon as a time of great deformation, a critical period in the history of North America. New lands were made by emergence from the sea, and old lands were deformed and made higher; new mountains were made, and old ones rejuvenated; streams were turned from their courses in some places, and nearly everywhere started on careers of increased activity. The fact that such notable changes, with increased elevation of land, occurred during the epoch next preceding the glacial period, is one of the considerations which led to the once wide-spread belief that the elevation was the cause of the climate of the latter period. While there may be a connection between the two things, it was probably not in the simple and commonly accepted sense.

The volcanic activity of preceding periods continued into the Pliocene, and became somewhat pronounced near the end of the period in different parts of the western Cordillera. Some of the late igneous formations of the Sierras, and perhaps of northern

¹ Smith, Ellensburg, Wash., folio, U. S. Geol. Surv.; and Willis and Smith, Professional Paper 19, U. S. Geol. Surv.

² Ashley, Jour. Geol., Vol. III, p. 434.

California,¹ belong to this time, and probably some of those of nearly or quite every other state west of the Rocky Mountains. Many of the prominent volcanic peaks of the west date from this time, or later, and represent the later phases of the prolonged period of volcanic activity, just as the great lava flows and intrusions represent the earlier. Many lesser cones belong to the same period.

Foreign

From considerable areas of Europe covered by water during the Miocene, the waters retreated late in the period or at its close; but the sea covered southern and southeastern England, Belgium, and parts of France during at least some portion of the Pliocene, and still more extensive areas of the present continent about the Mediterranean. Beyond the inland margins of the marine Pliocene, there are contemporaneous beds of terrestrial origin. In southeastern Europe, brackish and salt lakes came into existence, as shown by the fossils and the local deposits of salt and gypsum. In some places, as in the Vienna basin, brackish water beds below grade up into fluviatile beds above.

In Italy only do Pliocene beds attain massive development. Along the Apennines, their thickness has been variously estimated at from 1,600 to 3,000 feet, and in Sicily 2,000 feet. Limestone as well as clastic beds enter into the system, and occur up to heights of 3,000 feet.

Marine Pliocene is known in Egypt, where the sea is thought to have extended up the Nile to Assuan. The formation of the basins (*rifts*) of the Red Sea and the Gulf of Suez, has been assigned to this period, though the rift origin of these depressions has not been accepted universally.

THE LIFE OF THE PLIOCENE

The land plants. During the Pliocene there was a further sorting out of the mixed flora of previous periods, and the southerly migration of what are now tropical and subtropical plants continued. In southern France there were species identical with those

¹ Hershey, Jour. Geol., Vol. X, pp. 377-392.

now living in the Canaries. In Europe generally there was still much commingling of species now separated geographically. Some of this later separation is in longitude, and does not carry climatic suggestiveness. The evidence, on the whole, points to a general movement in latitude, in anticipation of the present distribution and adaptations of the plants.

The land animals. The history of the mammals continued to be the great center of interest. Three important features characterized it: (1) A notable intermigration of the continental faunas, including those of North and South America; (2) the initiation of the present divergence between Old and New World types; and (3) the culmination and perhaps initial decline of the placentals, the human and domestic species aside.

The intermigration of the early part of the period was a consequence of the land connections, not yet worked out in detail, brought about by deformative movements. The extent of the connection of North America with Eurasia at the northwest and northeast respectively is uncertain, but the evidence of good migratory routes for the land mammals during a portion of the period may be accepted as conclusive. There are also strong hints of the existence of a connection which afforded passage for some species, but not for others. The prohibition was perhaps the increasing cold in the later stages of the period, leading up to the glacial period which followed. The increasing cold, with its effect on intermigration, was perhaps the chief factor in developing the difference between the mammals of the Old World and the New.

The connection between North and South America introduced a biological movement of dramatic interest. There appears to have been no effective isthmian thoroughfare for land animals between the earliest Eocene and the Pliocene, when a way was opened. During the Eocene connection, a few North American mammals seem to have sent representatives into South America, and these had evolved on distinctive lines in the interval. A remarkable group of sloths, armadillos, and ant-eaters had developed from an edentate stem; strange hoofed animals of orders unknown elsewhere (*Typotheria*, *Toxodontia*, *Litopterna*) had arisen from some very primitive ungulate form; monkeys of the South American

type had evolved probably from a North American Eocene lemuroid, while rodents of the porcupine type had been derived from some unknown immigrant. That the connection of the continents in the Eocene was only partial or temporary, seems to be implied by the absence in South America of most of the great North American groups (creodonts, carnivores, condylarths, artiodactyls, perissodactyls, and insectivores). The absence of proboscideans implies a lack of connection between South America and Africa, where these forms developed during the Eocene and Miocene. Many carnivorous and herbivorous marsupials, similar to those of Australia,



Fig. 557.—Teeth of mastodon (*Mastodon longirostris*), showing slightly worn tubercles at the right and much worn ones at the left. (From Gaudry, after Kaup.)

lived at this time in South America, implying either connection in that direction, or striking parallel evolution. The remarkable South American mammalian fauna is a striking instance of evolution on a large scale in comparative isolation, and in relative freedom from the severe stimulus of effective competition, powerful carnivores, and shifting geographic relations.¹

When connection between the two Americas was made in Pliocene time, the fauna of each continent invaded the other. Horses, mastodons, deer, carnivores, llamas, and tapirs, from the north went to South America, while gigantic sloths from the south came to our continent, but did not maintain themselves long.

The *herbivores* continued to occupy the foremost place among mammals. Both the odd- and even-toed ungulates completed

¹ Reports of the Princeton University expedition to Patagonia 1896-99.

their deployment into present orders, and very generally into present genera. They were also represented by many genera and species which are now extinct. A list of Pliocene families would be little more than a catalogue of living ones. The evolution of the horse was advanced to the existing genus *Equus*. Giraffes and giraffe-like animals, some of them of great size, invaded southern Europe and Asia, coming probably from Africa.

The giants of the period were the *proboscidi*ans. The extinct *Dinotherium* was widely distributed in Europe and has been found



Vig. 558.—Teeth of elephant (*Elephas primigenius*), with the transverse ridges differentially worn, showing dentine in the center, the enamel, which forms the crenulated loops, supported by dentine within and cement without. (Owen and Metcalfe.)

in India, but is not known to have reached America. Mastodons seem to have occupied all the continents, but it is doubtful whether the elephant reached America before the Pleistocene. They appear to have flourished in Europe, and with the associated rhinoceroses and hippopotamuses, gave to the European fauna an African aspect.

The *carnivores* of both continents thrive and perhaps gained on the herbivores; at any rate they put a severe tax on the herbivores, forcing further progress in the line of alertness, sagacity, speed, and defense, and gaining similar qualities themselves. The *rodents* appear to have held about their present place relatively.

Supreme interest attaches to the development of the primates, but the data on this point are likely to remain limited until the tropical regions of the Old World are more fully studied, for the chief evolution of this group seems to have taken place there. No remains of lemuroids or of their descendants have been found in the Pliocene of North America. Those of Europe are from the

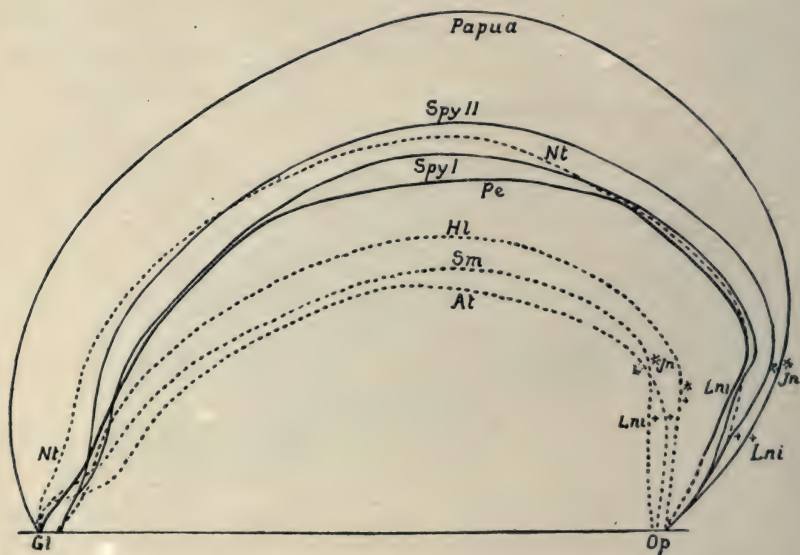


Fig. 559.—Profile of the skull of the *Pithecanthropus erectus* (line *Pe*) compared with profiles of the lowest men and highest apes; *Spy I* and *Spy II*, the men of Spy; *Nt*, the Neanderthal man; *Hl*, a gibbon (*Hylobates leuciscus*); *Sm*, an Indian ape (*Semnopithecus maurus*); and *At*, a chimpanzee (*Anthropopithecus troglodytes*). (After Marsh.)

middle and southern parts of the continent, a limitation which probably implies that northern Europe was already too cold for these animals.

The most interesting discovery of recent date is that of the remains of a man-like skeleton in Java, and named *Pithecanthropus erectus*. The relics include the roof of a skull, two molar teeth, and a femur. The form of the femur indicates that its possessor walked erect. The forehead was low and the frontal ridge prom-

inent, and in general the characteristic features were intermediate between those of the lowest men and the highest apes, as shown in Fig. 559. The size of the brain was about two-thirds that of an average man. The interpretation of this find has elicited much difference of opinion. By some the bones are thought to be those of an abnormal man; by others, those of an ancestral type between man and his more remote ancestry.

The marine life. The record of marine life on the Atlantic coast of America is extremely meager. The few forms which have been found in southern New England (Gay Head, Sankoty Head) show that species which then ranged from Bering Sea to the north Atlantic, are now confined to temperate latitudes.¹ On the coast of California the early Pliocene faunas indicate a temperature lower than that of the Miocene, while the later Pliocene faunas point to sub-boreal conditions.² On the other hand, Pliocene fossils from Alaska (vicinity of Nome) indicate for this locality, when the beds containing these fossils were deposited, a climate similar to that of north Japan and the Aleutian Islands, where the sea remains unfrozen, though Nome has now a sub-arctic climate. Similarly Pliocene fossils from the northwest coast of Iceland indicate a temperature no colder than 42° (mean) where conditions are now arctic.³ The apparent lack of harmony between the phenomena of California and higher latitudes may perhaps be due to the different horizons from which the fossils come.

Certain fossils of Japan and California indicate intermigration, or migration from a common center, sometime during the period.

Map work. Many of the folios mentioned on pp. 726 and 771 afford good sections of the Tertiary formations. In addition, the following folios may be mentioned: *Arizona*, Bradshaw Mountain; *Colorado*, Ouray; *Georgia*, Rome; *Idaho*, Boise, Silver City; *Kentucky*, Richmond; *Maryland*, Patuxent; *Nebraska*, Camp Clarke, Scott's Bluff; *Washington*, Tacoma, Ellensburg, Mt. Stuart, Snoqualmie; *West Virginia*, Huntington.

¹ Dall, Jour. Geol., Vol. XVII.

² Arnold, Ralph, Jour. Geol., Vol. XVII.

³ Dall, loc. cit.

CHAPTER XXX

THE PLEISTOCENE OR GLACIAL PERIOD

The distinguishing feature of this period is its extensive glaciation, ice-sheets covering six or eight million square miles of the earth's surface where mild climates had prevailed not long before. But for the ice-sheets and their effects, this period might properly be joined to the Pliocene, making one period of high and extensive lands and correspondingly restricted oceans.

General Distribution of Glaciation

More than half the area glaciated during the Pleistocene period was in North America (Fig. 560), and more than half of the remainder in Europe (Fig. 561). The glaciation was, therefore, notably localized, though the whole world felt its effects.

North America. Nearly half of North America was buried by ice (Fig. 560), and strangely enough, it was the northeastern half of the continent rather than the northern. More strangely still it was the plain, rather than the mountainous part, which had most ice. Alaska was largely free from ice except in the mountains, and continuous glaciation did not extend as far south on the mountain-girt plateaus of the Pacific border as on the smooth low plains of the Mississippi basin.

Three great *centers of ice radiation*, besides Greenland, have been recognized.¹ These are the Labradorean, the Keewatin, and the Cordilleran. From these centers, ice-sheets spread, covering some 4,000,000 square miles. The centers from which the movements radiated are determined with certainty by glacial striæ, and by the direction of transportation of drift.²

From the Labradorean center, the extension was notably

¹ A fourth center has been suggested. Wilson, *The Glacial History of Nantucket and Cape Cod*.

² This applies only to the radiations of the last glacial epoch.

greatest to the southwest, and in this direction the limit is some 1,600 miles from the center of dispersion, in latitude about $37^{\circ} 30'$, the most southerly point of the great lowland glaciation of the



Fig. 560.— Sketch-map showing the North American area covered by ice at the stage of maximum glaciation.

period. The extension of the Kewatin ice-sheet to the southward was scarcely less. It found its limit in Kansas and Missouri, about 1,500 miles from its center, while to the west and southwest it reached 800 to 1,000 miles toward the Rocky Mountains. One of

the most marvelous features of the ice dispersion was the great extension of the Keewatin sheet from a low flat center westward and southwestward over what is now a semi-arid plain, rising in the direction in which the ice moved, while mountain glaciers on the west, where now known, pushed eastward but little beyond the foothills.

The Cordilleran ice-sheet is less simply defined. Much of it occupied a plateau hemmed in by mountains, and plateau glaciation



Fig. 561.— Sketch-map showing the area of Europe covered by the continental glacier at the time of its maximum development. (Jas. Geikie.)

was complicated by extensive mountain glaciation of alpine type. In some sense, the whole Cordilleran ice-sheet was the product of a confluence of mountain glaciers deploying on the intervening plateau; but there appears to have been plateau glaciation not solely dependent on contributions of ice from the mountains. The southerly lobes of the complex body of ice crossed the boundary of Canada into the United States. Though hampered by its en-

vironment, the Cordilleran ice-sheet seems to have conformed to the habit of the Labradorean and Keewatin sheets in expanding chiefly to windward. The plains of Alaska seem to have been largely free from glaciation even when the waters of the Ohio and the Missouri, 2,000 miles farther south, were being turned from their courses by the ice-sheets. The localization of the glaciation is one of its most significant features.

South of the more or less continuous Cordilleran glaciation of Canada, *local glaciers* were widely distributed in the western mountains, even down to New Mexico, Arizona, and southern California. They were larger at the north and smaller at the south. Of glaciation in the mountains of Mexico little is known.

Greenland was glaciated somewhat more extensively than now, but its glaciers appear never to have extended to the continent, as was formerly conjectured. *Newfoundland* seems to have had its own ice-sheet, and the same was probably true of Nova Scotia, and perhaps of the peninsula between the Bay of Fundy and the lower St. Lawrence.

Other continents. South of the ice-sheets of Europe, great glaciers descended from the Alps to the lowlands in all directions, and lesser ones among the lower mountains. Iceland was buried in ice, and even Corsica had glaciers. In Asia glaciers larger than those of to-day affected all the higher mountains, and ice-sheets existed in some of the more northern lands. The southern hemisphere was affected to a lesser degree, but the higher mountains generally bore glaciers, and Antarctica is assumed to have been buried beneath ice as now. In tropical regions, there were glaciers in mountains where none exist now, and in mountains where there are glaciers, the ice descended then to levels 5,000 feet or more below its present limits.

The Criteria of Glaciation

The area of North America which was overspread by ice is covered by a mantle of clay, sand, and boulders, which taken together, constitute *the drift*. The various lines of evidence which have led to the general acceptance of the glacial theory, have to do with (1) the drift, (2) the surface of the rock which underlies

it, and (3) the relations of the drift to its bed. Some of the principal considerations are the following:¹

1. **The constitution of the drift.** One of the striking characteristics of the drift is its heterogeneity, both physical and lithological. It is made up at one extreme, of huge boulders (Fig. 562), and at the other of impalpable earthy matter. Between these ex-



Fig. 562.—“Pilot Rock.” A glacial boulder near Coulé City, Wash. (Garrey.)

tremes there are materials of all sizes, and the proportions of coarse and fine are subject to the greatest variations. Coarse materials are, on the whole, most abundant in regions of rough topography, where the underlying and neighboring formations in the direction from which the drift came are resistant; fine materials

¹ The phenomena pointing to the glacial origin of the drift have become so familiar that it is unnecessary to give extended references to the literature of the subject. They were emphasized in many of the early publications concerning the drift. The striae and other scorings of the ice are elaborated in the 7th Ann. Rept., U. S. Geol. Surv. The study of the drift from the standpoint of genesis is given in the Jour. Geol., Vol. II, pp. 708-724 and 807-835, and Vol. III, pp. 70-97, and in Glacial Geology of New Jersey, pp. 3-33. The geological Reports of all the states affected, and of Canada, contain descriptions of the phenomena.

are most abundant where the underlying formations and neighboring formations in the direction from which the drift came are weak. The fine part of the drift is made up chiefly of the same materials as the gravel and boulders, but of these materials in a fine state of subdivision. The coarse and the fine materials are often mixed without trace of assortment or arrangement.

The drift of any locality is likely to contain rock material from every formation over which the ice which reached that locality had passed; but the larger part of the drift of any place is of ma-



Fig. 563.— A large boulder in northwestern Illinois. (Carman.)

terials from formations near at hand. Probably 75% of the material of the drift was not moved 50 miles.¹ No agent except glacial ice can impress these precise features on the deposits which it makes.

2. Peculiarities of the boulders, etc., of the drift. The boulders and smaller stones of unstratified drift possess significant features. Many of them have smooth surfaces, but they are not generally rounded. They are often subangular, and the wear which they have suffered has been effected obviously by planing and bruising, rather than by rolling (Figs. 205 and 564). Some of these planed, subangular boulders and stones are distinctly marked with

¹ The Local Origin of the Drift, Jour. Geol., Vol. VIII, p. 426.

one or more series of lines or *striae* on one or more of their faces. The lines of each series are parallel, but those of different sets may cross at any angle. By no means all the stones of the drift show striae. They are rarely seen on those which have lain long at the surface, and they are more common on the less resistant sorts of rock, such as limestone, than on more resistant ones, such as



Fig. 564.—Stones of the drift, striated and beveled by glacial wear. (U. S. Geol. Surv.)

quartzite. No depositing agent except glaciers habitually marks the stones which it deposits in this way.

3. **Structure.** The larger part of the drift is unstratified, but a considerable part is stratified, often irregularly. The unstratified drift (Fig. 565) or *till* (for some of it the name *boulder-clay* is appropriate), has little orderly arrangement of its parts, yet it often has a sort of rude cleavage which has been called *foliation* (Fig. 566). The planes of cleavage are in such position as to suggest that they were developed by pressure from above. The stratified drift (Fig. 567) shows by its structure that it was deposited by water, which doubtless sprang, in large part, from the melting of the ice.

Either of the two great types of drift, the stratified and the unstratified, may overlies the other, or the two may be interbedded. The association of the two is often such as to demonstrate their essential contemporaneity of origin. No agents but glacial ice and glacio-fluvial waters could have brought about such relations be-

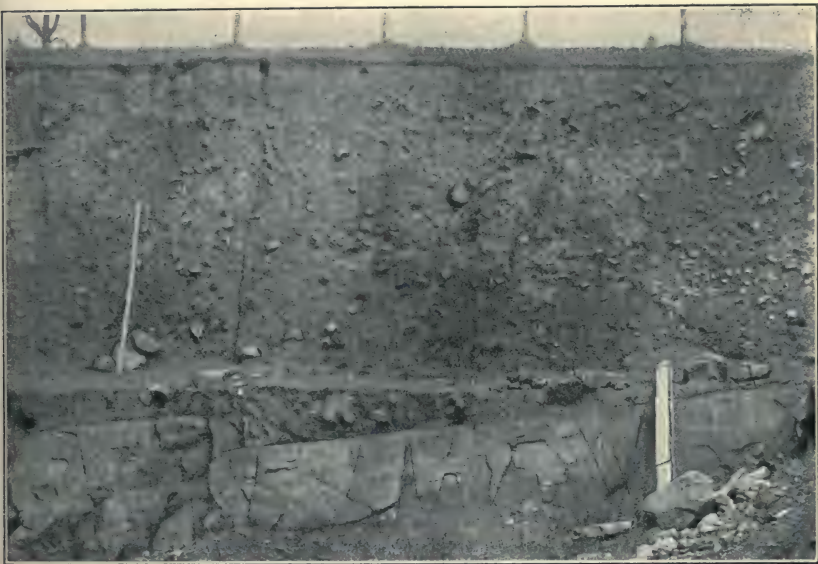


Fig. 565.— A section of unstratified drift — till or boulder clay, on bedrock. Newark, N. J. (N. J. Geol. Surv.)

tween the stratified and unstratified drift over such extensive areas.

4. **Distribution.** The distribution of the drift is essentially the same as that of the ice-sheets and glacial waters; but apart from this general fact, there are several special features to be noted. (a) Within the area of its occurrence, the drift is measurably independent of topography. That is, its vertical range is as great as the relief of the surface itself. Within the state of New York, for example, it ranges from sea-level to the tops of the Adirondacks, nearly 5,000 feet above. It is found in valleys and on hills, and

on plains, plateaus, and mountains, indiscriminately, though not usually in equal amounts. (b) The drift is sometimes so disposed as to make the surface rougher than it would be otherwise, and sometimes so as to give it less relief. This is illustrated by Figs. 568 and 569. (c) It is measurably independent of present drainage basins, so far as its constitution is concerned. Thus, materials from



Fig. 566.— Foliated till. (Photo. by Jefferson.)

one drainage basin are found in the drift of other drainage basins so commonly as to make it clear that present divides did not constitute divides to the ice. (d) Various sorts of material in the drift at certain points are so related to their sources as to make it clear that they were carried upwards, sometimes hundreds of feet, from their original sites. (e) A considerable area in southwestern Wisconsin, and the adjacent parts of Illinois, Iowa, and Minnesota, is without drift. This driftless area is neither notably higher nor lower than its surroundings, and glacial ice seems to be the only

agent which could have spared it, while covering its surroundings. (f) Stratified drift often extends beyond the unstratified in the direction in which the ice was moving, especially in valleys and on low land. This is the work of running water.

5. **Topography.** Among the characteristic features of the topography of the drift are: (a) Depressions without outlets, and (b) associated knobs, hills, and ridges, similar in size to the depres-



Fig. 567.— A section of stratified drift.

sions (Figs. 227 and 570). Many of the depressions contain ponds or lakes. The surface of some parts of the drift, on the other hand, is nearly plane. Neither planeness nor unevenness can be ascribed exclusively to the stratified nor to the unstratified drift. Either may be rolling, or either may be plane, though the phases of topography assumed by the two sorts of drift are somewhat unlike.

6. **Thickness.** The drift ranges from zero to more than 500 feet in thickness, and the variations are often great within short

distances. Within the glaciated area, one hill may be composed of drift, while the next has only an interrupted veneer of it. The drift may be thick on hills and thin in valleys, or, more commonly, the reverse. No agent besides glaciers habitually leaves its deposits so unequally distributed, and in such disregard of pre-existing topography.

7. Contact with underlying rock. The plane of contact between the drift and the rock beneath is generally, though not always,



Fig. 568.—Diagram to show how drift may be so disposed as to increase the relief of the surface. This should be compared with the following figure.

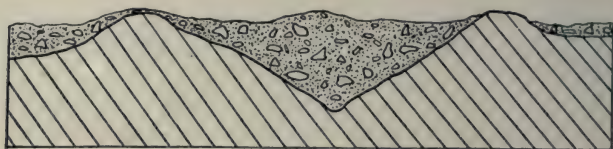


Fig. 569.—Diagram to illustrate how drift may decrease the relief of the surface.

sharply defined, and the surface of the rock is likely to be fresh and firm (Fig. 203, p. 252). This relation is in contrast with that between the mantle rock and the underlying formations where there is no drift (Fig. 210, p. 257).

8. Striation and planation.¹ The rock surface beneath the drift, and especially beneath the unstratified drift, is frequently polished, planed, striated (Fig. 203), and grooved. These features are wide-spread throughout the drift-covered area, and they occur at all elevations where the drift occurs. The striæ on the bed rock beneath the drift are generally approximately parallel in any given

¹ 7th Ann. Rept., U. S. Geol. Surv., pp. 155-248. An elaborate discussion of this topic.

locality, and tolerably constant in direction over considerable areas. When large areas are considered, the striae are sometimes far from parallel; but their departure from parallelism is generally according to a definite system (Fig. 571). The direction of striae corresponds with the direction in which the drift was transported.

Besides the striae, grooves, etc., on the bed rock, there are often other details of surface which are equally characteristic. Minute protuberances of surface often show more wear on one side than



Fig. 570.— Terminal moraine topography near Oconomowoc, Wis. (Wis. Geol. Surv.)

on the other (Fig. 572), and minute depressions (Fig. 573) show analogous features.

9. **The shapes of rock hills.** The rock knolls which were left bare when the ice retreated often show peculiarities of form and surface which are distinctive. Like the minute protuberances of surface just referred to, rock hills over which the ice passed were worn more on the side from which the ice approached (the stoss side) than on the other (Fig. 211, p. 257). Bosses of rock which do not show notably unequal wear often show distinct smoothing. Projecting glaciated knolls of rock which show the characters seen in Fig. 225, p. 269 are known as *roches moutonnées*. A succession of *roches moutonnées* generally gives fairly accurate information

as to the direction of ice movement, even though striæ are not preserved.

Summary. The characteristics of the drift, as set forth in the preceding paragraphs, leave little room for random speculation

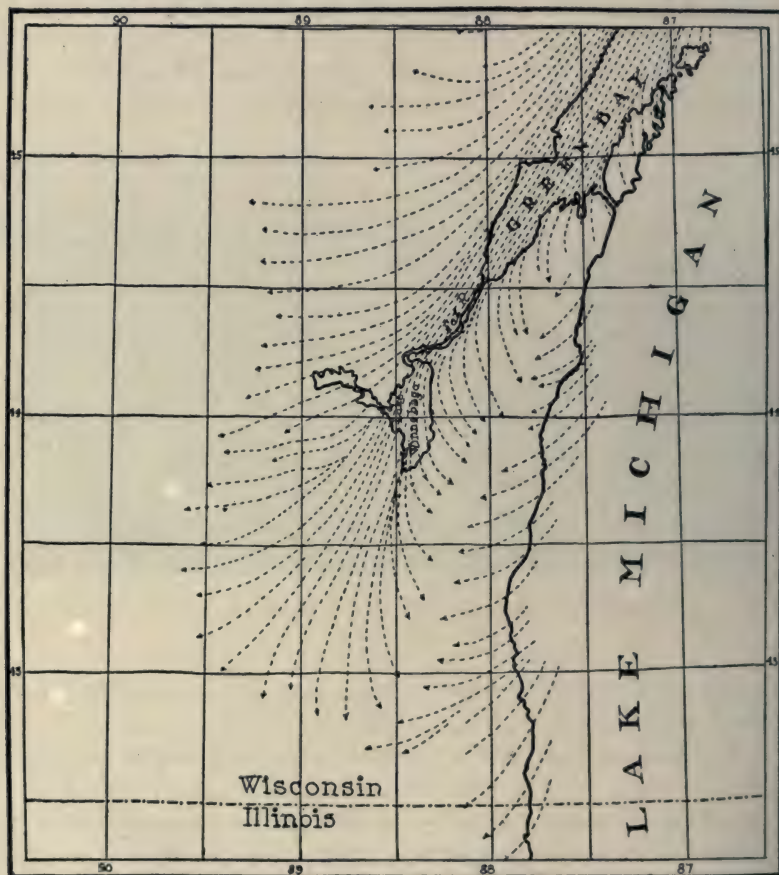


Fig. 571.—The radiation of striæ in the area of the Green Bay glacial lobe, and in the west part of the Lake Michigan lobe, during the last glacial epoch.

concerning its origin. From its variable thickness we know that the force or forces which produced it must have been such as could leave the drift now in thick bodies and now in thin, over either limited or

extensive areas. From its distribution we know that the force or forces which produced it were largely independent both of underlying rock formations and of topography. From its physical make up we know that the agency or agencies which produced it must have been able to carry and deposit, at one place and at one time, materials as fine as the finest silt or mud, and boulders many tons in weight, while they were competent, under other circumstances, to make deposits of much less extreme diversity. From its lithological make up, and from the nature of the finer parts of the drift, we know that the drift forces worked on different sorts of rock, deriving materials from many; that they ground some of the materials into a fine earthy powder or "rock flour," commonly called

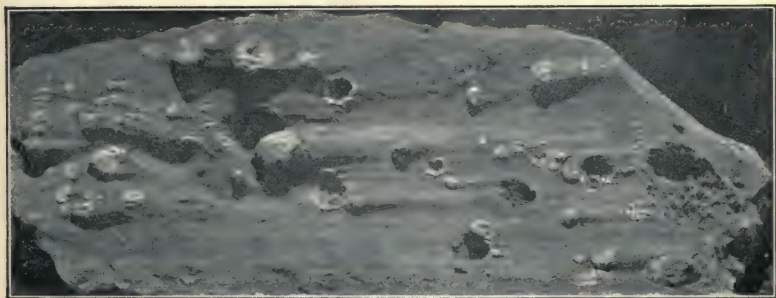


Fig. 572.— Small protuberances of rock showing the effect of ice wear. Glacial knobs and trails. The projections consist of chert in limestone. Near Darlington, Ind. (U. S. Geol. Surv.)

clay; that they as a rule derived the larger part of the drift of any locality from formations near at hand; and that the materials, even large boulders, were sometimes carried up to altitudes considerably above their source. From the structure of the drift it is concluded that the drift force or forces must have been capable of producing deposits which were sometimes stratified and sometimes unstratified, and that the deposition of these two phases of drift was sometimes contemporaneous and sometimes successive, the number of alternations being considerable in some places. From the striae on the stones of the drift it is known that the production of the drift must have involved the action of forces which, under some conditions,

were capable of planing and beveling and striating many stones, especially the softer ones of the unstratified drift, while rounding and leaving unstriated most of those of the stratified; but that the agency or agencies concerned must have been such that under certain circumstances their activities failed, on the one hand, to leave more than a very small percentage of the stones of the unstratified drift beveled and striated, while, on the other hand, they sometimes permitted the stratification of gravels containing many sub-angular, plane-faced, and striated stones, varying in size from pebbles to boulders. From the striæ on the bed-rock beneath the drift and the unweathered character of the surface of the rock, it is clear that severe wear was inflicted on the surfaces over which the drift was spread, while the positions in which the striæ were devel-



Fig. 573.— Diagram to show the effect of ice wear on slight depressions in the surface of rock.

oped show that the agency which inflicted the wear was able to adapt itself to all sorts of surfaces. The general parallelism of striæ in a limited area, and the systematic departure from parallelism over great areas, are also significant of the manner in which they were produced. From the topography of the drift it is known that the forces which produced it must have been such as were able to develop plane surfaces at some points, surfaces marked by more or less symmetrical drift-hills, which are measurably independent of rock-topography at others, and short, choppy hills, associated with undrained depressions, in still others.

The true theory of the drift must explain all these facts and relations. Any hypothesis which fails to explain them all must be incomplete at the least, and any hypothesis with which these facts and relations are inconsistent, must be false.

Geologists are now very generally agreed that glacier ice, supplemented by those other agencies which glacier ice calls into being, is the only agent which could have produced the drift. But it is

not to be forgotten that this does not preclude the belief that at various times and places, in the course of the ice period, icebergs may have been formed, or that locally and temporarily they played an important rôle. It does not preclude the idea that, contemporaneously with the production of the great body of the drift by glacier ice, the sea may have been at work on some parts of the present land area, modifying the deposits made by ice and ice drainage. Indeed, there is abundant evidence that such was the fact, for some regions, now covered by drift, stood lower than now, relative to sea level, when the drift was deposited, or since. The glacial theory does not deny that rivers produced by the melting of the ice were an important factor in transporting and depositing drift, both within and without the ice-covered territory. It does not deny that lakes formed in one way and another through the influence of ice, were locally important in determining the character and disposition of the drift. Not only does the glacier theory deny none of these things, but it distinctly affirms that rivers, lakes, the sea, icebergs, and pan-ice must have co-operated with glacier ice in the production of the drift, each in its appropriate way and measure, and that after the disappearance of the ice and the ice-water, the wind had some effect on the drift before it was clothed with vegetation.

The Development and the Thickness of the Ice-sheets

The development of glaciers from snow-fields has been discussed already (p. 229), but a few words with reference especially to the development of the ice-sheets of our continent, are here added.

If the expansion of the ice-sheets was due principally to movement from a center or centers, the ice at these centers must have been prodigiously thick, for in the course of its progress it encountered and passed over hills, and even mountains, of considerable height. In the vicinity of elevations which it covered, its thickness must have been at least as great as the height of these elevations above their bases.

If the centers of the North American ice-sheets remained the centers of movement throughout the glacial period, and if the degree of surface slope necessary for movement were known, the maximum

thickness of the ice could be calculated. It is probable, however, that the centers of the ice-sheet did not remain the effective centers of movement, and that the surface slope necessary for movement was variable.

If the fall of snow toward the margin of the ice-sheet greatly exceeded that at its center, as it probably did, a belt near the margin, rather than the geographic center of the field, may have controlled the marginal movement of the ice. With excess of accumulation near the border, the slope of the surface near the edge might be relatively great, while it was slight, or even nil in the center of the field, as shown by Fig. 574. Under these circumstances, the maximum

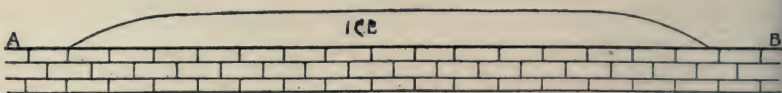


Fig. 574.—Diagram to illustrate the surface configuration of a great ice-sheet, according to the conception here presented. The central part is relatively flat, and the margins have steep slopes.

thickness of the ice-sheets might be notably less than if the geographic center remained the effective dynamic center. The former view is illustrated by Fig. 574.

No sufficient data are at hand for determining with accuracy the average slope of such an ice-sheet as that which covered our continent, but something is known of its slope at certain points. Near Baraboo, Wis.,¹ the edge of the ice at the time of its maximum extension in that region lay along the side of a bold ridge, the axis of which was nearly parallel to the direction of ice movement. The position of the upper edge of the ice against the slope of the ridge is sharply defined. For the last $1\frac{3}{4}$ miles, its average slope was about 320 feet per mile. This was at the extreme edge of the ice, where the slope was at a maximum. In Montana, the slope of the upper surface of the ice for the 25 miles back from its edge has been estimated at 50 feet per mile.² Half of this seems like a very low slope. A surface with a slope of 25 feet per mile would seem to the

¹ Jour. Geol., Vol. III, p. 655.

² Calhoun, Jour. Geol., Vol. IX, p. 718.

eye to be nearly plane; yet even so moderate a slope may lead to very extraordinary conclusions.

The southern limit of drift in Illinois is not less than 1,500 or 1,600 miles from the center of movement. An average slope of 25 feet per mile for 1,600 miles would give the ice a thickness of 40,000 feet at the center, the slope of the surface on which the ice rested being disregarded. This thickness, nearly eight miles, seems incredible. Even an average slope of 10 feet per mile would give a thickness of about three miles at the center. If by reason of relatively great precipitation near its margins, the only part of the ice-cap which had any considerable slope was its outer border (Fig. 574), so great a maximum thickness would not be demanded.

Stages in the history of an ice-sheet. The history of an ice-sheet which no longer exists involves two distinct stages. These are (1) the period of growth, and (2) the period of decadence. If the latter did not begin as soon as the former was completed, an intervening stage, representing the period of maximum ice extension is to be recognized. In the case of the ice-sheets of the glacial period, each of these stages was probably more or less complex, the general period of growth being marked by temporary intervals of decadence, while during the general period of decadence the ice was subject to temporary intervals of growth. In the study of the work accomplished by an ice-sheet, it is of importance to distinguish between these main stages.

THE WORK OF AN ICE-SHEET

Erosion and deposition were the two great phases of ice work, and both have been discussed briefly (pp. 251-68). It may be noted here that the surface over which the ice-sheets moved probably had an erosion topography, and was covered by a layer of mantle rock. The ice removed the mantle of decayed material, and cut deeply into the undecayed rock beneath. By its erosion, the ice modified the topography to some extent, for weaker formations were eroded more than resistant ones, the topography favored more forcible abrasion at some points than at others, and the ice itself

was more effective at some times and places than at others. On the whole, the topographic effect of glacial erosion was probably to soften the surface contours, without noticeably diminishing the relief.

The second great result of the ice-sheets was the deposition of the drift. Some of it was deposited while the ice-sheets were grow-

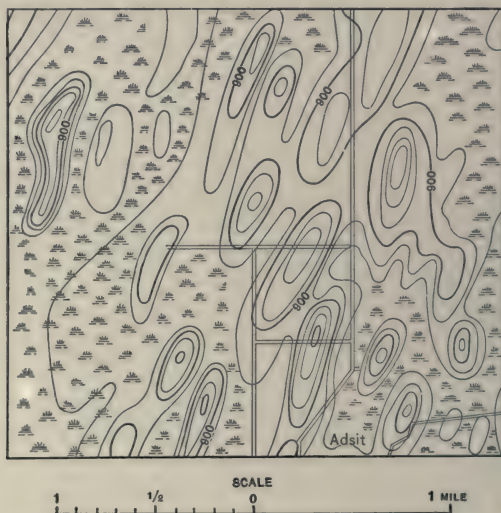


Fig. 575.—One phase of ground moraine topography; elongated hills of drift of the type shown here are called *drumlins*; southeastern Wisconsin. (U. S. Geol. Surv.)

ing, some of it after they had attained their growth, and some of it while they were declining. Some of it was deposited beneath the body of the ice, and some of it at its edge. The drift altered the topography notably, especially where it was thick and the relief of the underlying rock slight.

Formations Made by the Ice-sheets¹

The drift formations fall chiefly into three categories, namely (1) those made directly by the ice (unstratified), (2) those made

¹ Jour. Geol., Vol. II, pp. 517-538, and International Geol. Congr., 5th Session, 1893; also McGee, *idem*.

by ice and water conjointly (stratified, but stratification often irregular), and (3) those made by water emanating from the ice (stratified, often with cross-bedding).

Ground moraines, terminal moraines, and lateral moraines are the principal types of drift deposited by glaciers directly. So far as ice-sheets are concerned, ground moraines are the most extensive by far, and lateral moraines have little development.

The characteristics of *the ground moraine* are those usually given for drift in general. Ground moraine (or *till*) is nearly co-extensive with the ice-sheets themselves, though it failed of deposi-



Fig. 576.—A Wisconsin drumlin seen from the side; two miles north of Sullivan. (Alden, U. S. Geol. Surv.)

tion in some places, and has been removed in others. The ground moraine of the North American ice-sheets is thickest in a broad belt a little within the margin of the drift (Fig. 560), extending from central New York through Ohio, Indiana, Illinois, Iowa, Minnesota, and Dakota, and thence northward to an unknown limit in Canada.

The topography of the ground moraine varies within wide limits. It is commonly undulatory, involving gentle swells and sags (north-east half of Fig. 228). In some cases the swells take on rather definite elongate shapes, with their longer axis in the direction of ice movement. They are then called *drumlins* (Fig. 575). Drumlins have pronounced development in eastern Wisconsin, where they are numbered by the thousand, in central and western New

York, in some parts of New England,¹ and in some other places. The drumlins of New York (Fig. 577) are, in general, longer and narrower than those of Wisconsin.

The origin of drumlins has been much discussed without reaching a final conclusion. Opinion is chiefly divided between the views (1) that they were accumulated beneath the ice under special conditions, and (2) that they were developed by the erosion (by the ice) of earlier aggregations of drift.²

A *terminal moraine* is made where the edge of the ice remains nearly stationary in position for a considerable period of time. In constitution, it may be very like the adjacent ground moraine, though there is often a larger proportion of stratified drift associated with it. It sometimes constitutes a more or less well-defined ridge, but it is more accurately characterized as a belt of thick drift. Its most distinctive feature does not lie in its importance as a topographic feature, but in the details of its own topography. Its surface is often characterized by hillocks and hollows, or by interrupted ridges and troughs, following one another in rapid succession, and without apparent order (Figs. 227, 228, and 570). Many of the hollows and troughs contain marshes, ponds, and lakes. The shape and abundance of round and roundish hills, and of short and more or less serpentine ridges, often closely huddled together, have locally given rise to such descriptive names as "knobs," "short hills," etc.; but it is the association of "knobs" or "short hills" with "kettles," and not either feature alone, which is especially characteristic of terminal moraine topography.

The "knobs" vary in size, from low mounds but a few feet across, to considerable hills half a mile or more in diameter, and a

¹ For the topography of the drumlins, see the following topographic sheets U. S. Geol. Surv.: Wisconsin: Sun Prairie, Watertown, and Waterloo; New York: Oswego, Palmyra, Clyde, Brockport, and Weedsport; Massachusetts: Boston.

² Some of the more important papers on drumlins are: Upham, Proc. Bos. Soc. Nat. Hist., 1879, pp. 220-234, *ibid.*, Vol. XXIV (1889), pp. 228-242; Chamberlin, Third Ann. Rept., U. S. Geol. Surv., 1883, p. 306, and Jour. Geol., Vol. I, pp. 255-267; Davis, Am. Jour. Sci., Vol. XXVIII (1884), pp. 407-416; Salisbury, Glacial Geology of New Jersey, 1902; Lincoln, Am. Jour. Sci., Vol. XLIV (1892), pp. 293-296; Tyrrell, Bull. Geol. Soc. Am., Vol. I (1890), p. 402; Leverett, Monogr. XXXVIII and XLI, U. S. Geol. Surv., and Russell, Amer. Geol., Vol. XXXV (1905), p. 177.

hundred feet or more in height. Not rarely they are about as steep as the loose material of which they are composed will lie. The "kettles" are the counterparts of the elevations. They may be a

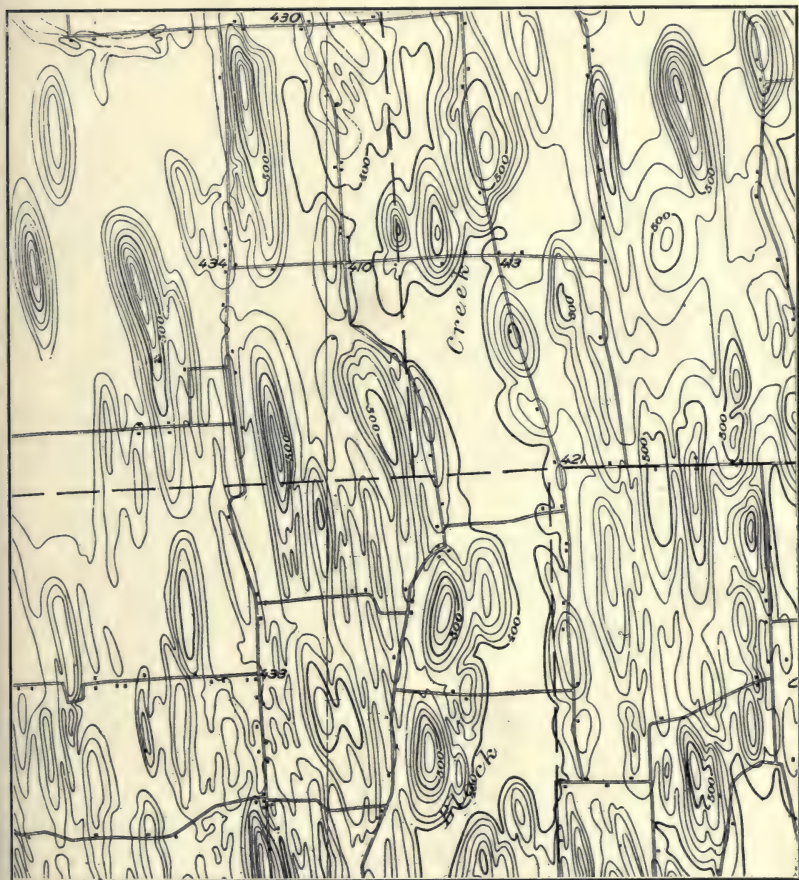


Fig. 577.— Drumlins in contour, near Clyde, N. Y. (U. S. Geol. Surv.)

few feet, or many rods, or even furlongs in diameter. They may be so shallow that the sagging at the center is scarcely observable, or they may be scores of feet in depth. Where steep-sided depressions are closely associated with abrupt hillocks, the topography

may be notably rough. The topography of the terminal moraine may be well developed, even where the moraine as a whole does not constitute much of a ridge.¹

The surface of the terminal moraine, where well developed, is generally rougher than that of the ground moraine, but more because the sags and swells are of smaller area and steeper slopes than because the relief is notably more. It is not to be understood,



Fig. 578.— Topography of drift shown in contours; an area near Minneapolis, Minn. Scale about one inch to the mile. (U. S. Geol. Surv.)

however, that this peculiar topography always affects terminal moraines, or that it is confined strictly to them. The elevations and depressions of the moraine may grade from strength to weakness, and locally may even disappear, while features closely simulating those characteristic of terminal moraines are sometimes found in other parts of the drift.

Where an ice-sheet halted in its retreat, its edge remaining in a

¹ References on terminal moraines: Chamberlin, Third Ann. Rept., U. S. Geol. Surv., 1881-2, pp. 291-402, and Amer. Jour. Sci., Vol. XXIV (1882), pp. 93-97; Salisbury, Glacial Geology of New Jersey, pp. 92-100 and 231-260.

constant or nearly constant position for a sufficiently long period, a terminal moraine (called a *recessional moraine*) was developed. The not uncommon impression that a terminal moraine is one which marks the *terminus of the drift*, is erroneous. The word terminal refers to the *terminus of the ice* at the time when it formed the moraine.

Fluvio-glacial Deposits

The waters arising from the melting of the ice-sheets organized themselves to a greater or less extent into streams before they left



Fig. 579.—Terminal moraine topography. (Alden, U. S. Geol. Surv.)

the ice.¹ Ultimately, the subglacial and englacial waters escaped from the ice, and when this took place, the conditions of flow were changed more or less suddenly, and deposits were made in several classes of situations.

1. **At the edge of the ice.** Where subglacial streams flowed under “head,” the pressure was relieved when they escaped from the ice, and decrease of velocity and deposition of load were the common results. In many cases, the deposits were made at the edge of the ice. After the ice melted, the deposits which had

¹ The general topic of ice drainage is discussed in *Glacial Geology of New Jersey*, p. 113 et seq., and *Jour. Geol.*, Vol. IV, p. 950 et seq.

been made against it and on its edge sometimes assumed the form of mounds, hillocks, and short ridges, known as *kames* (Fig. 580). Kames are primarily phenomena of the margin of the ice, developed by running water (the active agent) in association with ice (the passive partner). Kames are composed of stratified gravel and

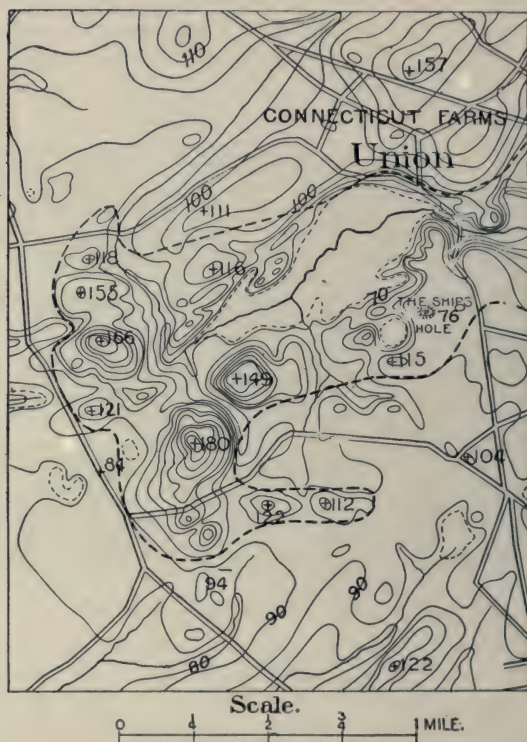


Fig. 580.—A group of kames near Connecticut Farms, N. J. (N. J. Geol Surv.)

sand chiefly, but the stratification is often very irregular, and the gravel ill-rounded. In position, kames have some relation to terminal moraines, and many of the conspicuous knobs and hills of such moraines are, individually, kames.

In regions of strong relief, ice often occupied deep valleys after it disappeared from the intervening ridges. In such situations the

ice sometimes seems to have lost vigorous motion, and drainage along its sides gave rise to deposits of stratified drift which, after the melting of the ice, had somewhat the form of terraces, while their slopes and upper surfaces had something of the topography of kames. Such terraces have been called *kame terraces*¹ (Fig. 581). Kame terraces are of frequent occurrence in the glaciated part of the Appalachian Mountains.

2. **Beyond the edge of the ice.** When the waters issuing from the ice found themselves in valleys, they aggraded their valleys in many cases, developing *valley trains*,² which often extended far beyond the unstratified drift with which they were contemporaneous. Valley trains are usually associated with stout terminal moraines (Fig. 230 p. 272).

Where the water escaping from the ice spread over a plain instead of being concentrated in valleys, the deposits took on a form



Fig. 581.— Diagram to illustrate kame terraces. *ABC* represents the stratified drift of the kame terraces which are underlain by ground moraine. Till also covers the valley bottom.

more like that of alluvial fans. By union, these fans often became extensive, making *outwash plains* (also called *overwash plains*, *moraine plains*, *frontal aprons*, etc.). When the water issuing from the ice flowed into standing water it tended to develop *deltas*. Many such deltas are known about extinct lakes, and about the borders of existing lakes, the levels of which have been lowered.

3. **Beneath the ice.** Subglacial streams seem sometimes to have deposited gravel and sand in their channels. Where such streams were confined to definite channels, and where their courses remained constant in position for a long time, the channel deposits stood out as ridges after the melting of the ice. Such ridges of gravel and sand are *eskers* (Fig. 231). It is not to be inferred that eskers never originated in other ways, but it seems clear that the aggradation of the channels of subglacial streams is the principal

¹ Salisbury, op. cit., pp. 156 and 121–124 respectively.

² 3d Ann. Rept., U. S. Geol. Surv., and Jour. Geol., Vol. I. p. 534.

method by which they were formed. The material of eskers is irregularly stratified. As in kames, the stratification is often much distorted, probably as the result of ice pressure. Boulders may be present in them and on their surfaces, showing the presence of the ice during their building. The best-developed eskers in the United States are in Maine.¹

4. **Deposits of superglacial and englacial streams.** Superficial and englacial streams have been supposed to make deposits in their channels, and it has even been conceived that eskers were the deposits in superglacial stream channels, let down from the ice when it melted. Against this view stand two facts: (1) So far as known, the surfaces of ice-sheets are free from drift except at their immediate edges,² and (2) superficial streams are, in general, much too swift to allow the accumulation of drift in their channels. The channels of most surface streams in North Greenland, *even near the edge of the ice where surface debris is abundant*, are free from drift. Judging from the force with which they issue from the ice, englacial streams too, are, as a rule, much too swift to allow deposition in their channels.

Relations of stratified to unstratified drift.³ The general relations of the stratified to the unstratified drift, already referred to (p. 852), may be understood when it is remembered (1) that the edge of each ice-sheet probably oscillated back and forth, more or less, during both its advance and its retreat, (2) that there were several successive ice-sheets over large parts of the area affected by drift, and (3) that stratified drift was being deposited at all stages of every ice-sheet, at points (a) beneath the ice, (b) at its edge, and (c) beyond it. These considerations explain why stratified drift is found underneath till, over till, and interbedded with it.

Topographic distribution of stratified drift. Though stratified drift is most abundant in valleys and on lowlands, it is not confined to these positions. Kames are measurably independent of valleys and lowlands, and though eskers often show a tendency to follow valleys, they often disregard topography to the extent of crossing

¹ Stone, Mono. XXXIV, U. S. Geol. Surv.

² Jour. Geol., Vol. IV, p. 804.

³ Jour. Geol., Vol. IV, pp. 948-970.

ridges and uplands a few hundred feet in height (200 to 400 feet in Maine)¹. Kame-terraces and deltas, also, are often well above the bottoms of the depressions with which they are associated.

Changes in Drainage Effected by Glaciation

The unequal erosion of the ice-sheets, but especially the irregular disposition of the drift, produced a profound effect upon the topography of the planer parts of the glaciated area. One result was the derangement of the drainage. This is seen in the thousands of lakes, ponds, and marshes which affect the surface of the drift. The basins of the lakes or ponds arose in various ways. There are (1) rock basins produced by glacial erosion; (2) basins due to the obstruction of river valleys by drift; (3) depressions in the surface of the drift itself; and (4) basins produced by a combination of two or more of the foregoing. Besides the lakes and ponds now in existence, others have become extinct by the filling of their basins or by the lowering of their outlets.

Glaciation also changed the courses of streams. In many cases, pre-existing valleys were filled with drift in some places, so that when the ice melted, the drainage followed courses which were partly new. In other cases, the ice, by encroaching on the middle course of a valley, as in the case of the Ohio, forced drainage around its front, and the drainage lines thus established were often held after the ice melted. There are few streams of great length in the area covered by the ice which were not turned from their old courses for greater or less distances by the ice or the drift. The Mississippi, the Ohio, and the Missouri, the master streams of the United States within the glaciated area, and a host of their tributaries, suffered in this way.²

¹ Stone, Mono. XXXIV, U. S. Geol. Surv., p. 434.

² For changes in the Mississippi and in the rivers of Illinois, see Leverett, Monogr. XXXIII, U. S. Geol. Surv., p. 120. For changes in the Upper Ohio, see Chamberlin and Leverett, Am. Jour. Sci., Vol. XLVII, 1894 (contains references to earlier work in this region). For changes in the Erie and Ohio Basin, see Leverett, Monogr. XLI, U. S. Geol. Surv., Chap. III, and Tilt, Professional Paper No. 13, U. S. Geol. Surv. For changes in the course of the upper Missouri and its tributaries, see Todd, Science, Vol. XIX, p. 148 (1892), Geol. of S. Dak., pp. 128 and 130 (1899), and Bull. 144, U. S. Geol. Surv. Changes in drainage in New York have been summarized by Tarr, Phys. Geog. of New York, 1902, with references to earlier literature.

The Succession of Ice Invasions

The glaciation of North America did not consist of a single ice invasion, but of a series of invasions separated by long intervals of time. It is not yet known how far the ice retreated in the intervals between the advances, but some of the interglacial intervals were much longer than the time since the last ice-sheet disappeared. There is also good evidence that in some of them the climatic conditions became at least as mild as they are to-day.

The proofs of the interglacial intervals and the evidences of their duration are found (1) in the erosion effected by streams after the deposition of one sheet of drift, and before the deposition of the next, (2) in the depths to which earlier sheets of drift were leached and oxidized by weathering before the deposition of later ones upon them, (3) in the accumulations of peat, soil, etc., now found between different sheets of drift, and (4) in the changes of topographic attitude which intervened between the deployment of successive ice-sheets.¹

The following are the American stages of the glacial period commonly recognized in the interior of North America, numbered in the order of their age:

- XI. The Champlain substage (marine).
- X. The glacio-lacustrine substage.
- IX. The Wisconsin, the fifth invasion, sometimes divided into two, an Early Wisconsin and a Late Wisconsin.
- VIII. The Peorian, the fourth interglacial interval.
- VII. The Iowan,² the fourth invasion.
- VI. The Sangamon, the third interglacial interval.
- V. The Illinois, the third invasion.
- IV. The Yarmouth, or Buchanan,³ second interglacial interval.
- III. The Kansan, or second invasion now recognized.
- II. The Aftonian, the first known interglacial interval.
- I. The sub-Aftonian, or Jerseyan, the earliest known invasion.

¹ Distinct glacial epochs and the criteria for their recognition, Jour. Geol., Vol. I, pp. 61-84.

² Question has recently been raised as to the reality of this drift-sheet.

³ The Buchanan gravels lie between the Kansan and Iowan drift-sheets, in localities where the Illinois is not present, and hence their age is not quite certain.

These stages were not equal. The early ones were longer and the late ones shorter.

I. The sub-Aftonian or Jerseyan glacial stage. In Iowa there is a very old drift-sheet lying beneath the Kansan drift. In the area of the Keewatin ice-sheet, this sub-Aftonian drift-sheet is not known at the surface, except as exposed by erosion. In Pennsylvania and New Jersey,¹ the frayed edge of a very old sheet of drift emerges from beneath the Wisconsin drift of the region, and is, perhaps, the equivalent of the sub-Aftonian of Iowa.²

II. The Aftonian interglacial stage. Overlying the oldest till is a stratum of sand and gravel at some points, and beds of peat and muck at others, with stumps and branches of trees. The surface of the drift below shows evidences of an interval of erosion and weathering. The organic remains in the interglacial beds indicate a cool temperate climate; but as a cool temperate stage must be passed through twice between successive glacial epochs, once as the ice retreats, and a second time as it advances again, organisms indicative of a cool climate do not necessarily show how warm the interglacial epoch may have become.

III. The Kansan glacial stage. The Kansan stage is represented by a sheet of till occupying a large surface area in Kansas, Missouri, Iowa, and Nebraska (Fig. 582). Theoretically it extends under the later glacial formations to the northward, as far back as the Keewatin center of radiation. Much of this sheet of drift, as originally developed, has probably been rubbed away by later glaciations. Presumably a similar sheet was formed by a contemporaneous ice-sheet spreading from the Labradorean center, but it has not been certainly identified. The Kansan drift is clayey till, with little stratified drift. Stream action seems to have been notably inefficient at this time. This and some other consonant facts have led to the abandonment of the former notion that vast floods inevitably accompanied the melting of the ice.

¹ Salisbury, Ann. Rept. of State Geol. of N. J., 1893.

² The Albertan "drift" (province of Alberta, Can.) formerly thought to be the probable equivalent of the sub-Aftonian, is probably not of glacial origin (Calhoun).

IV. The Yarmouth interglacial stage.¹ Where the Illinois till overlaps the Kansan (eastern Iowa), an old soil with deep subsoil weathering was formed on the surface of the latter before its burial.

V. The Illinois glacial stage. The exposed part of the Illinois drift appears at the surface in the southern and western portions of Illinois. It runs back under later formations to the northeast, toward the Labradorean center of radiation. It is not identified with any confidence east of Ohio, where its margin seems to have been overridden by the ice of the Wisconsin epoch. The identification of the Illinois drift in the Keewatin area is yet an open question. The Illinois till is clayey, with little assorted drift associated. The west edge of the Illinois ice-lobe pushed out into Iowa a score of miles, forcing the Mississippi in front of it.² The Kansan lobe had earlier invaded Illinois from the west, and probably forced the Mississippi east of its present course, if such an easterly course had not been taken before the Kansan epoch. Efforts to trace out the early courses of the Mississippi under the thick mantle of drift in Illinois and Iowa have not been entirely successful.

VI. The Sangamon interglacial stage.³ Like the preceding interglacial stages, this is marked by peat, muck, old soil and subsoil, weathering, surface erosion, etc., on the surface of the Illinois drift. Judged by these criteria, the interval was not as long as the Yarmouth.

VII. The Iowan glacial stage.⁴ The Iowan ice-sheet left a thin sheet of till (Fig. 582), marked by a profusion of large granitoid boulders many of which lie on the surface. The known Iowan drift was formed by a lobe of the Keewatin ice-sheet, which extended down into the north-central part of Iowa, but fell short of the Kansan invasion of the same region.

VIII. The Peorian interglacial stage.⁵ This is characterized in the same way as the preceding interglacial intervals, but less strongly.

¹ Leverett, Mono. XXXVIII, U. S. Geol. Surv.

² Idem.

³ Idem.

⁴ See Calvin, Bain, and others, Reports Iowa Geol. Surv. The reality of this sheet of drift as a separate formation has recently been called into question by Leverett.

⁵ Leverett, op. cit.

IX. **The Wisconsin glacial stage (or stages).** Following this epoch of readjustment, the ice radiated from the Labradorean, Keewatin, and Cordilleran centers (Fig. 560), and from many isolated heights. Nearly all the well-known mountain glaciation of the west is referred to this epoch. The margin of the ice-sheets assumed a pronounced lobate form, and the drift which they left is characterized by stout terminal moraines, numerous kames, eskers, drumlins, outwash aprons, valley trains, and other features distinctive of

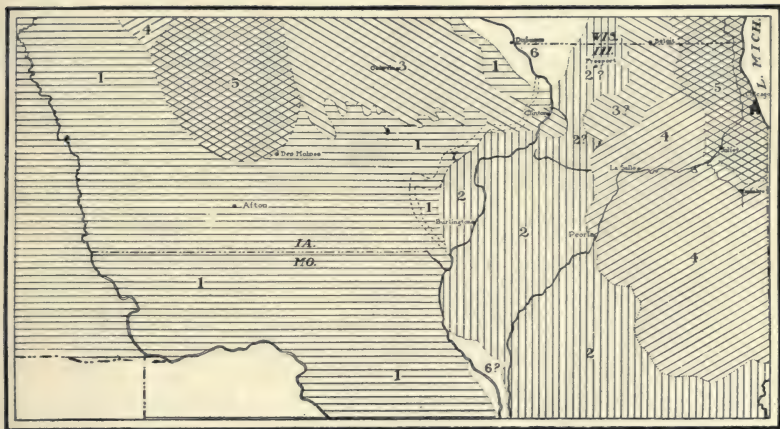


Fig. 582.—Map showing the relations of the several drift-sheets in Iowa and northern Illinois. 1, Kansan; 2, Illinoian; 3, Iowan; 4, Early Wisconsin; 5, Late Wisconsin; 6, Driftless area; 7, Course of the Mississippi during the Illinoian glacial epoch. (Leverett, U. S. Geol. Surv., and Calvin, Ia., Geol. Surv.)

glacial action and glacio-fluvial co-operation. This drift-sheet, far beyond all the others, bears the stamp of the great agency of the period. The pronounced topographic expression of this formation is in contrast with the relatively expressionless surfaces of the older sheets of drift. A part of this difference is due to the greater freshness of the Wisconsin formation; but the larger part, apparently, is assignable to a stronger original expression.

The Wisconsin glacial epoch has been divided into two, an Earlier and a Later. They are, however, less distinct than the other epochs mentioned above, and so are grouped together here.

The disposal of the ice in great lobes is referable to the influence of the great basins. Field studies indicate that broad, smooth-bottomed basins, elongate in the general direction of ice movement, favored the prolongation of the ice into broad lobes, while sharp, deep valleys of tortuous course or transverse attitude had little effect upon the extension of the ice. A study of Fig. 560 will make clear the relation between the great ice-lobes and the broad, smooth valleys lying under or back of them.

The Later Wisconsin drift has nearly a score of concentric terminal moraines in some places.¹ Some of these represent re-advances of the ice in the course of its general retreat, and others perhaps nothing more than halts sufficient to permit an exceptional

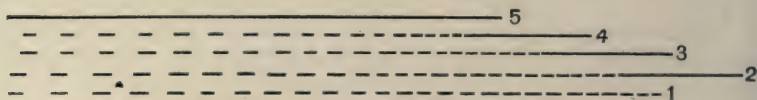


Fig. 583.— Diagram illustrating the imbrication of the successive sheets of drift. The full lines represent the portion of the drift-sheets not over-spread, or but little over-spread, by later ice-sheets; the broken lines represent the portions of the successive drift-sheets which were covered by ice at a later time. 1 corresponds to Jerseyan or sub-Aftonian, which in general is less extensive than the Kansan, though locally, as in New Jersey, it extended farther south than any other; 2 represents the Kansan drift, the southern margin of which is not covered by younger drift; 3, 4, and 5, respectively, represent the Illinoian, Iowan, and Wisconsin sheets of drift.

accumulation of drift at the ice border. The older drift-sheets, so far as overridden by the ice of this epoch, were cut away more largely than in preceding epochs, and the scoring of the rocks below was more prevalent and profound.

Not all of these several sheets of drift have been seen in superposition, and the history sketched is based on the relations of the sheets of drift at different points.² Theoretically, and perhaps really, the several sheets of drift are imbricated as shown in Fig. 583; but each sheet of drift is discontinuous beneath the overlying one, and this discontinuity goes so far that beneath the Wisconsin

¹ Minnesota, Upham, 9th Ann. Rept., Geol. and Nat. Hist. Surv. of Minn., 880; Leverett, Mon. XLI, U. S. Geol. Surv.

² Jour. Geol., Vol. I, pp. 61-84.

drift, for example, the several sheets are more commonly wanting than present.

X. The glacio-lacustrine substage. In the course of the retreat of the ice of the Wisconsin epoch, a complex series of lakes arose between the ice border on the one hand, and the higher land fronting it on the other. Many of these lakes were temporary and shifting, and had shifting outlets. Thus as the ice border receded north of the divide separating the St. Lawrence basin from the Mississippi basin, glacial waters were ponded between the ice on the north and the divide on the south. This gave rise to many lakes, the history of which cannot be given here; but a brief sketch of the history of the Great Lakes will indicate the nature of the changes which took place.

When the end of the Lake Michigan ice-lobe (Fig. 584) withdrew a little from the southern end of the Lake Michigan basin, a lake formed about its southern end, and found a point of discharge into the Illinois valley southwest of Chicago. The outflowing waters eroded its channel to greater depths, and it has since become the site of the Chicago drainage canal.¹ The glacial lake (Lake Chicago) thus initiated was gradually extended northward (Fig. 585) as the ice-lobe was melted.

A similar lake was formed about the head of the Lake Superior ice-lobe, and discharged to the Mississippi. Lake Maumee was formed about the end of the Erie ice-lobe, and discharged its waters by way of Fort Wayne into the Wabash, and thence to the Gulf. A later stage of Lake Chicago and Lake Maumee is shown in Fig. 585, when, finding a lower outlet as the ice melted back, Lake Maumee sent its outflow across southern Michigan to Lake Chicago.

Somewhat later, Lake Saginaw developed about the end of the Saginaw ice-lobe, and discharged by way of Grand River into Lake Chicago, and thence to the Mississippi. Lake Maumee then discharged into Lake Saginaw.

¹ This valley appears to have served a similar function in earlier stages of glacial retreat; but it was not the preglacial outlet of the Lake Michigan basin, as there are much lower channels (now buried) both north and east of it. One of these must have been the preglacial outlet of the Lake Michigan basin.



Fig. 584.—The beginning of the Great Lakes. The ice still occupied the larger parts of the present lake basins. (U. S. Geol. Surv.)



Fig. 585.—A later stage in the development of Lakes Chicago and Maumee. The ice has retreated, and the outlet of Lake Maumee has been shifted. (U. S. Geol. Surv.)

Later, the whole Erie basin, and a portion of that of Ontario, was freed of ice, and a lake twice the area of the present Lake Erie (Lake Arkona) developed. An advance of the ice changed the lake and in its changed outline it is known as Lake Whittlesey (Fig. 586).

With further retreat of the ice, the ponded waters in the Saginaw basin became confluent with those in the Erie basin, which had, in the meantime, become extended into the borders of the Ontario basin, but were blocked in that direction by the Ontario ice-lobe. The extensive water-body thus developed is known as Lake Warren (Fig. 587). At first, this lake discharged across Michigan into Lake Chicago, but later, when the Mohawk valley was freed from ice, it offered the lower outlet, and the level of Lake Warren was drawn down, and it was divided into two lakes, Erie and Iroquois (Fig. 588).

Meantime, the glacial lakes in the basins of Lake Michigan and Superior experienced analogous shiftings of areas and of outlets. While Lake Iroquois was discharging through the Mohawk valley, Lake Algonquin (Fig. 588), formed by the coalescence of the glacial lakes of the Superior, Michigan, and Huron basins, was discharging its waters eastward. At first the outlet was probably by the St. Clair-Erie route, through Lake Iroquois, to the Mohawk; but later, when the ice had retired farther north, an outlet appears to have been effected from Georgian Bay, via the Trent River to Lake Iroquois.

When at length the ice withdrew from the Adirondacks so far as to permit the waters of Lake Iroquois to find an outlet lower than that by way of the Mohawk, a new series of lowerings of the lakes followed. At first the outlet seems to have skirted the Adirondacks and emptied into a glacially-ponded water-body (glacial Lake Champlain) that occupied the Champlain basin, and discharged southward into the Hudson. Later the outlet was to the Champlain arm of the sea presently to be noted. By this time Lake Algonquin had given place to the great Nipissing Lakes (Fig. 589), which had their outlet via Lake Nipissing to the Ottawa, and thence to the Champlain arm of the sea. Subsequently the outlet was



Fig. 586.—A later stage in the development of Lakes Chicago, Maumee, and Saginaw. (Leverett and Taylor, U. S. Geol. Surv.)



Fig. 587.—Illustrating the relations of standing water to the ice in the Erie and Ontario regions after the ice had retreated farther than represented in Fig. 586. The numerous lobate lakes south of the Ontario lobe of ice will be noted, and also the fact that the discharge of Lake Warren was still to Lake Chicago. (Taylor and Leverett, U. S. Geol. Surv.)

shifted to its present position, probably by a gentle upwarping of the surface at the north.¹

Similar complicated histories doubtless attended the retreat

¹ An account of the history of the Great Lakes, by F. B. Taylor, is found in *Studies in Indiana Geography*. See also Goldthwaite, *Bull. XVII, Wisconsin Surv.*, and *Bull. VII, Geol. Surv. of Ill.*



Fig. 588.—The Great Lakes at the Algonquin-Iroquois stage. The outlet to the sea is by way of the Mohawk Valley. (Taylor.)



Fig. 589.—A still later stage of the Great Lakes. The sea is thought to have covered the area shaded by lines at the east. (Taylor.)

of the ice in the Mackenzie and Hudson Bay basins, but little is yet known regarding them.

A very important lake was formed in the Red River valley of the North (Lake Agassiz, Fig. 590), discharging, in its earlier history, into the Minnesota River at Lake Traverse. Lake Agassiz was not connected with the complex system of basins of the St. Lawrence valley, and had a comparatively simple history. It grew to the northward with the retreat of the ice which held it in at that end, and continued to discharge into the Minnesota River until the retreat of the ice gave it a northerly outlet. It developed beaches while it discharged to the southward, and another set after the outlet was northward. On the final withdrawal of the ice, the lake was drained.

The evidence which demonstrates the existence of these expanded lakes is found chiefly in the deposits which they made, and in the topographic features which they developed about their shores. Many of the former shore-lines have been traced in detail, and most of them depart notably from horizontality. In general, they rise to the north and northeast.

It is probable that there were corresponding lacustrine sub-stages at the close of each of the several glacial epochs, but their history is not known.

XI. The Champlain substage.¹ The significant feature of this stage is represented in Fig. 589, which represents an arm of the sea extending up the St. Lawrence to Lake Ontario, filling the basin of Lake Champlain, and probably connecting southward by a narrow strait along the site of the Hudson valley with the ocean. The sediments deposited in this arm of the sea contain shells and bones of marine animals. The marine fossils are found at various places about Lake Champlain at altitudes varying from 400 feet or less about the south end of the lake, to 500 feet at the north end, and about 600 feet near the east end of Lake Ontario.²

¹ Peet, *Jour. Geol.*, Vol. XIII (1904), pp. 415-469, 617-661; Salisbury, *Glacial Geol. of N. J.*, pp. 196-200; also Ries and Merrill, 10th Ann. Rept. N. Y. State Geologist, 1890; Ries, *Bull. N. Y. State Mus.*, Vol. III, 1895; Baldwin, *Ann. Geol.*, Vol. XIII, 1894; Davis, *Proc. Bos. Soc. Nat. Hist.*, Vol. XXV, 1891; Upham, *Bull. Geol. Soc. Am.*, Vol. III, 1891; Kellogg, *Science*, Vol. XIX, 1892; and Woodworth, *Bull. 84, N. Y. State Mus.*

² Dawson, G. M., *Am. Jour. Sci.*, 3d ser., Vol. VIII (1874), p. 143; Dawson, J. W., *The Canadian Ice Age*, p. 201, and *Am. Jour. Sci.*, Vol. CXXV, 1883.

At about the same time the sea stood higher than now relative to the land on the coast of Maine, where marine shells occur up to elevations of 200 feet or more,¹ and to still greater heights farther north.

The Loess

The term loess is used both as a textural and a formational name. Lithologically, it is a silt intermediate between sand and clay. It is generally free from stones of all sorts, except the concretions



Fig. 590.— Map of the extinct Lake Agassiz, and other glacial lakes. Lake Winnipeg occupies a part of the basin of Lake Agassiz. (U. S. Geol. Surv.)

developed in it since its deposition. In the exceptional cases where stones occur in it, they are confined to its very bottom, or are found in loess which has slumped or been washed down from its original position. It is sometimes interstratified with sand, especially at its base where it is thick. On slopes and at their bases loess is often mingled with slope wash, talus, etc.

¹ Dana, *Manual of Geology*, 4th ed., p. 982; and Stone, *Jour. Geol.*, Vol. I, pp. 246-254, and Bastin, *Rockland, Me. folio*, U. S. Geol. Surv.

Composition.¹ The loess contains angular, undecomposed particles of the commoner carbonates (calcite and dolomite) and silicates (feldspars, amphiboles, pyroxenes, micas, etc.), and several of the rarer silicates have been identified. Magnetite also is a common, though never an abundant, constituent. All these are subordinate to quartz. These constituents strongly suggest that the



Fig. 591.— A section of loess in Iowa, showing its ability to stand with vertical or even overhanging faces. (Calvin.)

material of the loess was derived from the flour of the glacial mill. In color it is predominantly buffish brown, but in not a few places it has a grayish (bluish) cast a few feet below the surface.

The loess often stands with vertical faces (Fig. 591) for long periods, where sand or clay would be degraded into slopes. Roads on the loess tend to assume the form of little canyons, because the

¹Sixth Ann. Rept. U. S. Geol. Surv., p. 281.

silt of the road-bed is washed or blown away, while that on either side stands up with steep or even vertical slopes. Weathered faces of the loess often show a rude columnar structure (Fig. 591), the columns being one to several feet in diameter. The loess, as a rule, shows no stratification, but in its coarser phases there is often some suggestion of such structure, and where interbedded with sand, stratification is sometimes distinct.

Distribution. The best known loess in America and Europe is associated with glacial formations, though the loess extends far beyond the borders of the drift in some directions, in both continents. In China and other lands of Asia,¹ where loess has its greatest known development, it is not generally associated with glacial formations.

In North America the loess does not occur east of the Mississippi basin, and has no great development east of the Wabash River. It is wide-spread in Illinois and the states along the Missouri, and in the states along the Mississippi farther south. Within this area, its distribution is peculiar in that it follows the main streams that led away from the Iowan drift-sheet, and is found especially on the bluffs overlooking the valleys. On this account it was formerly known as the *Bluff formation*. In this bluff-position, it has more than its average thickness and coarseness of grain, and grows thinner and finer in grain back from the river bluffs until it is lost in a vanishing edge. At the same time, its material loses its distinctive characteristics.

Just south of the borders of the Iowan and Wisconsin drift-sheets, it mantles many of the divides between the main streams; but farther south it is more confined to the valley borders. It has little regard for topography, and can hardly be said to have an upper limit. Within the the drift-covered part of the Mississippi basin, it occurs (1) as a surface mantle overlying drift, and (2) between sheets of drift. South of the drift there are in places distinct sheets of loess, sometimes separated by a well developed soil zone. The surface of the lower sheet shows the effects of prolonged weathering

¹ Von Richthofen, China. This author early (1877) advocated the eolian origin of the loess of China, but this explanation has not passed unchallenged. See Skertchly and Kingsmill, Q. J. G. S., Vol. LI, 1895, pp.238-254. Willis, *Researches in China*, Vol. I, Carnegie Institution.

and oxidation,¹ in some places. Loess occurs in isolated spots even as far west as Washington and Oregon.²

Age. The relations of the loess to the several drift-sheets make it clear that it was accumulated at different stages of the glacial period, but within the glaciated area the accumulation at one of these stages exceeds that at all others, both in volume and areal extent. The loess deposited at this stage is often referred to as "the loess," and is usually correlated in time with the Iowan drift. It is at least later than the Illinois sheet of drift which it mantles, and earlier than the Wisconsin drift which overlies it. Locally, a thin mantle of loess overlies the Wisconsin drift, even its later parts.³ No considerable body of loess older than the Illinois drift is known.

Thickness. The loess of the Mississippi basin rarely attains a thickness of more than a score or two of feet, and this only along the main valleys; but exceptionally its thickness approaches 100 feet. Thicknesses of 10 feet are much more common than greater ones.

Accessories. The loess contains characteristic accessories of two kinds, namely, concretions and fossils. The concretions are of lime carbonate and iron oxide. Many of the former are irregular and of such shapes as to have been called "petrified potatoes"; but many of them have other shapes. The ferruginous concretions take various forms, one of which is the "pipe stem," perhaps formed about rootlets. The fossils are chiefly gastropods (Fig. 592), almost exclusively of land species, or of such as frequent isolated ponds.⁴ There is, however, a lowland silt formation classed by some as loess, in which fresh-water fossils are found. The other fossils are bones and teeth of land mammals.

Origin. There has been much diversity of opinion as to the origin of the loess, the fundamental question being whether it is aqueous or eolian. There is little doubt that the loess-like silts which occur in the terraces of rivers are of fluvial origin; but some

¹ Report on Crowley's Ridge, Ark. Geol. Surv., pp. 224-235.

² Jour. Geol., Vol. IX, p. 730.

³ Jour. Geol., Vol. IV, pp. 929-937.

⁴ Shimek, Geol. Surv. of Ia., Vol. IV, pp. 929-937, and Loess Papers, Bull. Labr. Nat. Hist., Univ. Iowa, 1904.

would not regard them as loess. Some, indeed, would so define loess as to make it an eolian product.

By the aqueous hypothesis, the loess is assigned to direct deposition by rivers, or their lake-like expansions. To make this pos-



Fig. 592.—Loess Shells. *a-b*, *Zonitoides minusculus* (Binney); *c-d*, *Euconulus fulvus* (Drap.); *e-f*, *Strobelops labyrinthica* (Say); *g*, *Polygyra clausa* (Say); *h*, *P. multilineata* (Say); *i-j*, *Succinea obliqua* Say; *k*, *S. avara* Say; *l-m*, *Polygyra monodon* (Rack); *n*, *Bifidaria pentodon* (Say); *o*, *B. corticaria* (Say); *p*, *B. muscorum* (Linn.); *q*, *B. armifera* (Say). The small figures adjacent to some of the large ones show the natural size of the shells.

sible it is necessary to suppose that the waters stood at elevations 200 to 600 feet higher than now, relative to adjacent surfaces, in the Mississippi basin. This involves difficulties that have never been satisfactorily met. Furthermore, if the waters of rivers or

their lake-like expansions were high enough to cover the areas overspread by loess, it is not clear that there could have been an appropriate habitat for the land fauna of the time.

Under the eolian hypothesis, or at least one phase of it, the river flats are supposed to have supplied the material of the loess, which was whipped up by the winds and re-deposited on the adjacent uplands. The rivers are thus made essential factors in the distribution, though not the direct agents of deposition. This hypothesis seems on the whole to best fit the phenomena of the larger part of the upland loess of the Mississippi basin. The constituents of the loess, which appear to have come from the glacial drift, were derived largely from the deposits made by glacial waters, or from later flood plain silts derived from the glacial formations; but it is probable that some of the loess was derived from glacial drift directly, before it became clothed with vegetation.¹

The Duration of the Glacial Period

The desire to measure the great events of geological history in terms of years increases as the events approach our own time. The uncertainties attending such measurements are, however, so great that the results have an uncertain value, and do little more than indicate the order of magnitude of the time involved. Attempts to determine the date and duration of the glacial period fall mainly into two categories: (1) Estimates of the relative duration of the several glacial and interglacial epochs, and (2) estimates in years of the time since the close of the glacial period.

1. The best data for estimating the relative duration of the

¹ *References.* Loess is described in the geological reports of the following States: Iowa, Illinois, Missouri, Arkansas (Report on Crowley's Ridge), Kentucky (Report on Jackson Purchase Region), Tennessee, Louisiana (1899 and 1902), Mississippi (1854 and 1860), Minnesota (Vol. I, and Report for 1880), South Dakota (Bull. I), and Nebraska (Vol. I). Other references are Pumpelly, *Am. Jour. Sci.*, Vol. XVII, 1879; McGee, *Eleventh Ann. Rept.*, U. S. Geol. Surv.; Chamberlin and Salisbury, *Sixth Ann. Rept.*, U. S. Geol. Surv.; Todd, *Bull. Phil. Soc. of Wash.*, Vol. IV, *Bull. Geol. Soc. of Am.*, Vol. V, and *Science*, N. S., Vol. V; Shimek, *Am. Geol.*, Vols. XXVIII and XXX, *Bull. Ia. Lab. Nat. Hist.*, Vols. I, II, and V, *Proc. Ia. Acad. Sci.*, Vols. III, V, VI, and VII; Leverett, *Am. Geol.*, Vol. XXXIII, and *Monog. XXXVIII*; Calvin, *Bull. Geol. Soc. Am.*, Vol. X, p. 119; Chamberlin, *Jour. Geol.*, Vol. V, 1897; Davis, *Explorations in Turkestan*, 1905; and Willis, *Researches in China*, Vol. I, Carnegie Institution.

several glacial stages are found in the central basin of the Mississippi, for here only are all members of the series present. The criteria that have been used in estimating relative duration embrace (1) the amount of erosion of the drift, (2) the depth of leaching, weathering, and decomposition of its materials, (3) the amount of vegetable growth in interglacial intervals, (4) the climatic changes indicated by interglacial and glacial floras and faunas, (5) the times needful for the migration of faunas and floras, particularly certain plants whose means of migration are very limited, (6) the time required for advances and retreats of the ice, and some others. A few of these, as the first, are subject to direct measurement; but most of them are matters of judgment.

The average of the estimates of five glacial geologists who have most studied the data, is shown in the following table:

From the Late Wisconsin ¹ to the present,	1	time-unit.
From the Iowan to the present,	3 to 5	"
From the Illinoian to the present,	7 to 9	"
From the Kansan to the present,	15 to 17	"
From the sub-Aftonian to the present,	x	"

2. Of the efforts that have been made to measure in years the post-glacial interval, those based upon the recession of Niagara and St. Anthony Falls are the most significant.² It is important, however, to note precisely what is being measured. In both these instances, the measurement attempted is the time occupied in the recession of the falls from their starting point to their present positions. It is as important to know when they began their gorge cutting, as to know how long they have been occupied in it. The

¹ See IX, p. 874.

² *References on Niagara*: Gilbert, Am. Jour. Sci., 3d ser., Vol. XXXII, 1886; Science, Vol. VIII, 1886; Proc. Am. Assoc. Adv. Sci., Vol. XXXV, 1887; Rept. N. Y. Com. State Res. at Niagara, 6th Rept., 1890, Chapter in Physiography of the United States, and Bull. U. S. Geol. Surv. Upham, Am. Jour. Sci., 3d ser., Vol. XLV; Jour. Geol., Vol. I, 1893; Am. Geol., Vol. XI, 1893, and XVIII, 1896, and Pop. Sci. Mo., Vol. XLIX, 1896. Spencer, Am. Jour. Sci., 3d ser., Vol. XLVIII, 1894, Am. Geol., Vol. XIV, 1894, and *Evolution of the Falls of Niagara*; and Taylor, Bull. Geol. Soc. Am., Vol. IX, p. 84.

St. Anthony Falls: Winchell, N. H. Fifth Ann. Rept. Natl. Hist. and Geol. Surv. of Minn., 1876; Geol. of Minn., Vol. II, 1888, 23d Ann. Rept., 1894; Southall, *The Epoch of the Mammoth*, p. 373.

gorge cutting of the Niagara Falls could not have begun until the Mohawk outlet of the lakes (p. 883) was abandoned, because the escarpment through which the cutting subsequently took place was submerged while Lake Iroquois discharged through the Mohawk valley. The time measured by the Niagara cutting is only that which has elapsed since the ice retired from the north flank of the Adirondacks far enough to permit the waters of the ancestral Lake Ontario to find an outlet lower than the Niagara escarpment, and no very effective cutting could take place until the waters were withdrawn to something near their present level.

If the border of the ice-sheet at this stage (Fig. 588) is compared with the border of the ice at the maximum Wisconsin stage, it will be seen that it had retreated some 600 miles, and it cannot be assumed that the retreat was an uninterrupted one.

Before attempting to place a value upon the period so represented, the time at which the gorge below St. Anthony Falls began to be cut may be considered. It is to be presumed that for a time after the retreat of the ice-edge north of the site of these falls, the Mississippi valley was being aggraded, for the outflowing drainage must be presumed to have been overburdened with glacial detritus. In support of this assumption is the abundant evidence that the Mississippi valley, as far down as the mouth of the Chippewa River, was filled with detritus to a depth of more than 100 feet. Farther south the glacial filling appears to have been 80, 70, 60, and 50 feet above the river, the last in the latitude of central Illinois.

When fluvio-glacial aggradation of the Mississippi valley ceased, it was necessary for the river to clear out its trench before effective cutting of the gorge below the falls could begin. Under any probable hypothesis, there must have been a retreat of the ice some 700 to 800 miles from its extreme extension (to Des Moines) during the last glacial epoch, before the cutting began. The rate of recession is unknown, but 200 feet per year is an improbably high rate. At this rate, the ice must have been receding well toward 20,000 years, before the falls began. If the retreat of the ice previous to the beginning of the cutting of the Niagara gorge is taken at 600 miles, the time occupied, on the assumption of a retreat of 200 feet per year, is about 15,000 years.

If the length of the Niagara gorge be divided by the average annual retreat since the successive positions of the falls were located by accurate surveys, the quotient is about 7,000. This result is, however, subject to several qualifications, chief of which is the fact that at the time of the beginning of the cutting of the gorge, the waters of the upper lakes flowed by a more northerly route to the sea, leaving only the waters of the Erie basin to pass over the falls. If the history is correctly read, it was only at a comparatively late date that the waters of the Upper Great Lakes went out through the Niagara River. These and other considerations have led Gilbert, Taylor, Spencer, and others to the view that the cutting of the narrower portion of the gorge was probably the work of the lesser volume of water from the Erie basin, and that the recession at this stage proceeded at a relatively slow rate, but that the rate of recession was accelerated when the upper lakes began to discharge their waters to Lake Erie. It is this accelerated rate that is used as the divisor in the simple computation that gives 7,000 years. In view of these considerations, it is thought that 7,000 should be multiplied several times to give the true time-estimate. Spencer places the period at about 39,000 years, and Taylor at 50,000 years as an approximate maximum. There are, however, those who do not accept the conclusions, and who appeal to other phenomena that cannot be discussed here.

From a comparison of the earlier and later surveys of St. Anthony Falls, the time of recession from the mouth of the gorge has been estimated at about 8,000 years. But considerations not taken into account in this estimate, make it clear that this estimate should be increased to 12,000 or 16,000 at least.

It will be seen therefore that even in these cases of best data, there are possible errors, and that these errors may affect the results to the extent of several hundred per cent. If the range of the estimates for Niagara Falls be placed at 10,000 to 50,000 years, and if this be added to the range of estimates for the time of retreat of the ice before the falls came into existence, 10,000 to 30,000 years more, the result is 20,000 to 80,000 years for the time since the beginning of the Late Wisconsin ice retreat. These may be taken for a rough, wide-ranging estimate of the time since the climax of the Late Wis-

consin ice invasion. Using the estimates in the table of relative duration above, and remembering that we are multiplying such errors as there may be in the previous estimates, we reach the following dates for the climaxes of the several ice invasions:

Climax of the	[Late] Wisconsin	20,000 to	80,000	years ago.
" " "	Iowan	60,000 to	400,000	" "
" " "	Illinois	140,000 to	720,000	" "
" " "	Kansan	300,000 to	1,360,000	" "
" " "	sub-Aftonian	y to	z	" "

Little value is to be placed on estimates of this kind, except as means for developing a conception of the order of magnitude of the time involved.

Foreign

In Europe, the succession of ice epochs and formations is not less complex than in North America, though there is not complete agreement among geologists as to the number of glacial epochs.¹ In the Alps four glacial epochs are recognized.² These are designated³ Günz (pre-Kansan?), Mindel (Kansan?), Riss (Illinois?), and Würm (Wisconsin?). The glacial formations of other continents have not been studied in detail, in many places, but recent studies in Turkestan indicate that there were several glacial epochs in the Thian Shan Mountains.⁴

THE CAUSE OF THE GLACIAL PERIOD

Many hypotheses of the cause of the glacial period have been offered, but none commands universal assent. Most of them appeal to a combination of agencies, but each centers on some one factor which gives character to the hypothesis. They fall mainly into three classes: (1) those based on elevation of the land, the *hypso-metric hypotheses*; (2) those based on phenomena and relations outside the earth itself, the *astronomic hypotheses*, and (3) those based

¹ Geikie, Jour. Geol., Vol. III, pp. 241-269. Keilback, *ibid.*, vol. III, pp. 113-125.

² Penck, Die Alpen im Eiszeitalter.

³ Penck, Science, Vol. XXIX, p. 359.

⁴ Huntington, Explorations in Turkestan, Carnegie Institution.

on changes in the constitution, movements, or cloud-content of the air, the *atmospheric hypotheses*.

Hypsometric Hypotheses

The hypothesis of elevation.¹ Since the best-known glaciers are in mountains, the suggestion was natural that elevation of the glaciated regions was the cause of the great ice-sheets. The chief evidence of the elevation postulated is the submerged valleys of the sea-coasts, especially those of the northern latitudes. It has been held by advocates of this hypothesis that 4,000 feet or more of elevation is indicated by the northern fiords, and that this elevation, together with accompanying geographic changes, was competent to produce the Pleistocene glaciation. Those who question this view doubt the fact of so great elevation, and doubt whether any elevation which there may have been was contemporaneous with the ice-sheets. Further, they offer evidence that the land was lower than now at certain important stages of the glacial period. The elevation hypothesis also encounters difficulty in explaining the interglacial intervals, now well established, and in accounting for the markedly mild climate of some of them. The hypothesis, in its simple and popular form, would seem to require a great elevation of a large part of two continents, for each ice epoch, and a great depression for each interglacial epoch. This can hardly be granted. On the whole, this hypothesis has lost rather than gained favor, as evidence has accumulated.

Astronomic Hypotheses

Croll's hypothesis.² A semi-astronomical hypothesis was advanced by Croll in the latter part of the last century. For a time it was widely accepted, especially in Europe. It is founded primarily on variations in the eccentricity of the earth's orbit, combined with the precession of the equinoxes.

The orbit of the earth is slightly elliptical, and this ellipticity is

¹ Dana, *Manual of Geology*, 4th ed., p. 970, and Upham, *Am. Geol.*, Vol. VI, p. 327, and *Am. Jour. Sci.*, Vol. XII, p. 33.

² *Climate and Time in their Geological Relations*; a theory of secular changes of the earth's climate, by James Croll, 1890, pp. 312-328; also *Climate and Cosmology*, 1889, and *The Cause of the Ice Age*, Sir Robt. Ball, 1893.

subject to considerable variation. This does not alter the total amount of heat received by the earth, or by either hemisphere, from the sun; but it affects the *distribution* of heat within the year, shortening or lengthening the cooler and warmer seasons, according as they fall in the perihelion or the aphelion part of the earth's orbit. Thus the hemisphere which has summer in perihelion has a short summer with much heat per hour; the other hemisphere has a long summer with less heat per hour. The precession of the equinoxes reverses the seasonal relations of the hemispheres every 10,500 years. At present the earth is nearest the sun in winter in the northern hemisphere (summer in the southern hemisphere). In 10,500 years the earth will be nearest the sun in the summer of the northern hemisphere (winter of the southern hemisphere). We shall then have a shorter summer with more solar heat per hour than now, and a longer winter with less heat per hour. Croll's hypothesis is built upon the belief that snow-accumulation would be favored by long winters, and snow-melting reduced by short summers. The hypothesis is that the glacial epochs were the times of aphelion winters during periods of great eccentricity.

It is admitted that these astronomical relations are insufficient in themselves to produce the observed glaciation, and so certain terrestrial conditions are made important elements in the working force of the hypothesis. Thus it is held that the zone of the trade-winds and the thermal equator would be shifted from the glaciated hemisphere toward the warmer one, and that this shifting would turn a large part of the warm equatorial waters away from the cooler hemisphere. Croll held that if the trade-wind belts were shifted southward a few degrees, a large part of the equatorial current would be south of Cape St. Roque, and so turned into the South Atlantic, greatly lowering the temperature of the northern hemisphere. When the southern hemisphere was passing through its cold period, nearly all the equatorial current would be north of St. Roque, and this would give the northern hemisphere a moist interglacial epoch.

If the hypothesis were correct, (1) glacial epochs should alternate between the northern and the southern hemispheres, and (2) their duration should be limited to an appropriate fraction of the pre-

cessional period (21,000 years). This appropriate fraction is probably about that which effective winter bears to the whole year. In the middle latitudes, the effective period of cold would perhaps be 5,000 or 6,000 years; in the high latitudes, one-half or more of the precessional period. These peculiarities of the hypothesis afford a means of testing it. If it be true, the glacial episodes should bear evidences of equal length; they should all be short, and all of those in the same period of eccentricity, equally distant from each other in time. If the computed periods of eccentricity are correct (which has been questioned), there could only be a few alternations of glaciation between the hemispheres within a given period of high eccentricity, while none of them could be more recent than 60,000 years; indeed, Croll placed the close of the glacial period 80,000 years ago.

The glacial studies of recent years seem to show that the intervals between the different invasions are of very unequal duration, and that the most recent is relatively young. It has also been found that glaciation was extended notably beyond its present limits on the lofty mountains of the equatorial regions, though this climate should not have been much affected. The Labradorean and Keewatin ice-sheets pushed out from what appear to have been their centers about 1,600 and 1,500 miles respectively. If one foot per day be allowed for the advance of the margin — an estimate much beyond the probabilities — it would take more than 20,000 years for the ice-edge to reach the extension observed. This is nearly the whole of the precessional period. Nor is the difficulty escaped by assuming that the snow-field grew up simultaneously over the whole area, or some large part of it, for numerous bowlders are found 600 to 1,000 miles from their probable sources. To allow time for the residue of winter snow above summer melting to build itself up to a height capable of giving effective motion, and then to allow time to carry drift this great distance at any probable rate of motion, taxes the hypothesis very severely, to say the least. On the whole, the result of prolonged study of the hypothesis has been to weaken, rather than strengthen it.

Other astronomical hypotheses. Attempts have been made to base other theories on the eccentricity of the earth's orbit, and

also on variations in the obliquity of the ecliptic; but none of them has gained much acceptance. They encounter most of the difficulties of the Crollian hypothesis, in somewhat different forms. There have been speculations upon the possible passage of the earth through cold regions of space, but there is no astronomical basis for them.

The hypothesis of a wandering pole. It was early suggested that the axis of the earth may have been shifting its geographic position, and that the Pleistocene glaciations were but polar glaciations of the existing type, at a time when the north pole was 15° or 20° south of its present position. So long as the theory of a thin crust resting on a liquid nucleus, and capable of sliding over it, was accepted, the mechanical difficulties of this hypothesis did not seem insuperable; but if the earth is essentially rigid, as seems almost certain, the dynamic objections to the hypothesis seem fatal to it. The distribution of the ice-sheets of the earlier glacial epochs also raises objections to this as a general theory.

Atmospheric Hypotheses

Hypotheses have been based on the direction of the prevailing winds and also upon the degree of cloudiness; but these have not been satisfactorily connected with known causes and with the conditions prevailing in Pleistocene times. Furthermore they have not been worked out into detail so as to fit the facts of periodicity and localization, facts which all hypotheses must meet before they can have serious claims to acceptance. Winds and clouds were no doubt factors in glaciation.¹

The leading hypothesis of the atmospheric class is based chiefly on a postulated variation in the constituents of the atmosphere, especially in its amount of carbon dioxide and water. Both these elements have high capacities for absorbing heat, and both are being constantly supplied and constantly consumed. Periods of great land elevation, extension, and erosion are periods of great consumption of carbon dioxide, for, on account of the great contact which the exposed surface presents, the carbon dioxide takes part in the decomposition of rock in a large way. So also, at times of

¹ Manson. Am. Geol., Vols. XIV, XXIII, and XXIV.

great land elevation and extension, the sum total of evaporation of water was reduced, and the average amount of water vapor in the air was correspondingly lowered. The great elevation of land at the close of the Tertiary seems to afford conditions favorable both for the consumption of carbon dioxide in large quantities, and for the reduction of the water content of the air. Depletion of these heat absorbing elements was equivalent to the thinning of the thermal blanket which they constitute. If it was thinned, the temperature was reduced, and this would further decrease the amount of water vapor held in the air. The effect would thus be cumulative. The elevation and extension of the land would also produce its own effects on the prevailing winds and in other ways, so that some of the features of the hypsometric hypothesis form a part of this hypothesis. This hypothesis also takes into account the action of the ocean in absorbing and giving forth carbon dioxide under the varying conditions that prevailed. It is thus a highly complex hypothesis and cannot be fully set forth here.¹

By variations in the consumption of carbon dioxide, especially in its absorption and escape from the ocean, the hypothesis attempts to explain the periodicity of glaciation. Localization is attributed to the two great areas of permanent low pressure in proximity to which the ice-sheets developed.

While this hypothesis is still new and on trial, it is almost if not quite the only one which has been worked out into details so far as to fit the leading facts as now developed by studies of the glacial formations. It should be understood, however, that its truth remains to be established, and that modifications and additions may yet be required.

FORMATIONS OUTSIDE THE ICE-SHEETS

While the glaciation of middle and high latitudes was the most striking event of the Quaternary period, by far the larger part of the earth's surface was not affected directly by the ice, and outside

¹ For a fuller exposition of this hypothesis see Chamberlin and Salisbury's *Earth History*, Vol. III, pp. 432-446.

the area of glaciation, the commoner phases of erosion and deposition were in progress, and non-glacial Pleistocene formations are wide-spread. Under the varied conditions of the period, various classes of deposits were made, among which were the following: (1) *Eolian deposits*, conspicuous along many shores and rivers, and in sundry arid regions, and inconspicuous as dust over much larger areas. (2) *Fluviatile deposits*, made by streams (a) with and (b) without connection with the ice. These deposits occur along most streams of low gradient, and along many others. Kindred deposits were made by sheet-floods and temporary streams, even far from the courses of permanent streams. (3) *Lacustrine deposits* of both the glacial and non-glacial types, made in existing lakes and about their borders, and also over the sites of the numerous lakes which have become extinct since the beginning of the period. (4) *Deposits made by springs*. (5) *Terrestrial organic deposits* (peat, calcareous marl, etc.) occur outside the area directly affected by the ice, but are more common in the ponds and marshes to which glaciation gave rise. (6) *Marine deposits*, on lands submerged during the Pleistocene period, and doubtless over essentially all of the ocean bottom. (7) *Volcanic rocks* of Pleistocene age are found in our continent, chiefly west of the Rocky Mountains, though volcanic dust is widely distributed on the Great Plains. All these kinds of deposits were doubtless made at other periods, but have not been so generally preserved.

The average thickness of the Pleistocene deposits is not great. Glacial drift and Pleistocene accumulations of debris at the bases of mountains are sometimes several hundreds of feet thick; but otherwise the thickness of non-glacial Pleistocene deposits rarely exceeds a few score feet.

On the Atlantic and Gulf Coasts

On the Coastal Plain of the Atlantic and the Gulf of Mexico, there is a wide-spread but thin body of gravel, sand, loam, and clay, referred to the Pleistocene period. It ranges from sea-level up to altitudes of several hundred feet, though most of it lies below 200 feet. All of the non-glacial post-Tertiary deposits of the Atlantic and Gulf plains were formerly grouped together under the name

Columbia; but the materials formerly grouped under this name represent at least three somewhat distinct stages of deposition.¹

The oldest subdivision of the Columbia series is found at levels higher than those of the younger subdivisions. In the principal valleys, it constitutes broad but often rude terraces, which rise up-stream. Up the Potomac, the Susquehanna, the Delaware, and other valleys, the terraces rise to altitudes notably above those attained by the formation outside the valleys. In New Jersey this member of the Columbia series is called the *Bridgeton formation*.

In the District of Columbia, the second member of the Columbia series covers rock terraces 100 feet or so below the oldest member phase of the series (Fig. 593). The relations of the two subdi-

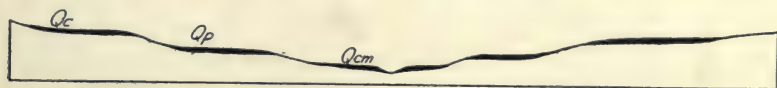


Fig. 593.—Diagram showing the relations of the three divisions of the Pleistocene as seen in valleys. *Qc* = the high-level Columbia, *Qp* = the low-level Columbia (or Pensauken), and *Qcm*, the Cape May formation.

visions indicate that extensive erosion followed the deposition of the first, and that the broad valleys then developed were subsequently aggraded by sediments similar to those of the preceding epoch of deposition. The two deposits are so nearly alike in composition that their separation is based chiefly on their topographic relations. This member of the Columbia series is called, in New Jersey, the *Pensauken formation*.

The third phase of the composite Columbia is found at still lower levels along the streams and coasts. Its disposition is such as to show that the second phase of the Columbia formation had been somewhat extensively eroded before the deposition of the third. In the valleys formed during this interval of erosion, and along the coast at accordant levels, the third member of the series finds its chief development. Outside the valleys, the landward edge of this member of the series is as ill-defined as the landward edge of the older members in the inter-stream areas. In New

¹ Reports of the State Geologist of New Jersey, 1897-1900; also Philadelphia folio U. S. Geol. Surv.

Jersey, this member of the Columbia series is called the *Cape May formation*. Fig. 594 shows, diagrammatically, the supposed relations of the three phases along an interfluvial tract, from the coast inland.

The various members of the Columbia series rest unconformably on older formations. On the Atlantic Coast, the older divisions often rest on the Lafayette formation, and often on terranes from which the Lafayette had been eroded before the deposition of the Columbia series (Fig. 595).

Fossils. The Columbia series rarely contains fossils; but at a few points shells of fresh-water mollusks have been found in the Pensauken a few feet above sea-level. Marine shells have been



Fig. 594.—Diagram showing the theoretic relations of the three principal subdivisions of the Pleistocene outside the valleys, along a line normal to the coast. The letters have the same significance as in Fig. 593.

found in gravels which are perhaps of Pensauken age, on the east coast of New Jersey. Such evidence as the few fossils afford, therefore, is against the marine origin of at least parts of the formation. The Cape May formation, like the older Pleistocene formations of the Atlantic Coast, is generally without fossils, but marine shells have been found in it at a few points (southern New Jersey) a few feet (10 or less) above sea-level.

The origin of the Columbia and associated formations. The origin of the Columbia formation presents much the same problems as that of the Lafayette, and is probably to be explained in much the same way; that is, the series is looked upon as largely subaërial (pluvial and fluvial), the result of land aggradation. The occasion for renewed deposition on the Coastal Plain in the Quaternary period probably lay (1) partly in changes of gradient incident to surface warpings, and (2) partly in the changes of climate of the period. Slight further upward bowing of the highlands west of the coast probably stimulated the streams descending from them

to increased erosion, and the deposition of a part of their loads on the plain below was a natural result. The poor assortment of the material, the common cross-bedding, the numerous trifling unconformities, and the absence of fossils, all are consistent with this interpretation.

The second factor contributed to the same end. The climate



Fig. 595.—Unconformable contact between the Columbia formation and the Potomac, Washington, D. C. (Darton, U. S. Geol. Surv.)

of the period was changeable, and at least periodically cold, as the recurrent ice-sheets show. Under these conditions a larger proportion of the precipitation than now was doubtless in the form of snow, and this was favorable to the flooding of streams during the melting seasons. Floating ice helped to transport the boulders of the formation, and so to give it the heterogeneity which is one of its distinctive features, especially in proximity to the glacial drift. The cold climate probably affected erosion, and therefore

deposition, in another way, for the reduction of temperature was probably attended by a reduction of vegetation, and an increase of erosion. The reduction of vegetation was probably greatest just where erosion was most readily stimulated, namely, in the higher altitudes.

It is conceived, therefore, that the deposition of the principal subdivisions of the Quaternary series of the Coastal Plain resulted from the combined effect of slight surface warpings and climatic changes; that epochs of notable deposition alternated with epochs when erosion was dominant in the same regions; and that the materials of each principal stage of deposition were deposited, shifted, and re-deposited repeatedly, so that the Bridgeton, the Pensauken, and the Cape May formations are each really complex series, though they nowhere attain great thickness.

While the Cape May division of the Quaternary was being deposited, the sea transgressed some parts of the present coast to a slight extent, at the same time that deposition was taking place in the valleys scores of miles inland, and in some cases hundreds of feet above sea-level. If similar relations existed during the earlier stages of Quaternary deposition, the seaward edges of the deposits of each principal stage of deposition may be marine. It is probable also that the series contains estuarine phases of sedimentation, and it can hardly be doubted that each subdivision now recognized on the land has its synchronous marine phase beneath the sea.

The Cape May formation was essentially contemporaneous with the last glacial epoch, and it seems not improbable that the earlier members of the Quaternary system of the coast were made during earlier glacial epochs.

In recent times, dunes have been developed at numerous points along the coast, and their development and destruction is still in progress.¹ Humus deposits also have somewhat extensive development in the tidal marshes, and to a less extent elsewhere.

In the Interior

Some of the non-glacial Pleistocene formations of the interior, notably the loess, the valley trains, etc., have been referred to.

¹ See for example, the Norfolk, Va.-N.C., folio, U. S. Geol. Surv.

Apart from such formations, there are others which seem to be measurably or wholly independent of the ice. The wide-spread gravels of the western plains have been referred to (p. 829), but their deposition continued into the Pleistocene, and is indeed still in progress. There are numerous tracts and belts of dunes where conditions favor their development, as in central Nebraska,¹ and some parts of Kansas. Dunes are of common occurrence locally even east of the Great Plains, as about the head of Lake Michigan and along its eastern shore. Even where dunes are wanting, wind-blown sand and dust in small quantities are wide-spread.

Outside the region affected by the ice-sheets, erosion rather than deposition was the great feature of the Quaternary in the interior. In the erosion, wind, running water, and ground-water have co-operated.

In the West

The Quaternary formations of the west belong to all the several categories mentioned on p. 900, and in addition there is much glacial drift left by mountain glaciers. Few of these various sorts of deposits have received close study over any considerable area, though something is known of all. The deposits of some of the lakes at various points west of the Rocky Mountains, especially those of the Great Basin, deserve special mention.

Lacustrine deposits. The most considerable of the western Pleistocene lakes was *Lake Bonneville*² (Fig. 596) of which Great Salt Lake is the diminutive descendant. Its basin is believed to have been due to deformation and faulting. Previous to the formation of the lake, the basin is thought to have been arid, a conclusion based on the great alluvial cones and fans subsequently covered by the lake. During the pre-lacustrine period of aridity, such quantities of debris from the surrounding mountains were brought into the basin as to bury the bases of the mountains to depths of perhaps 2,000 feet, at a maximum.

Later, climatic conditions became such as to bring a large lake

¹ Darton, 19th Ann. Rept., U. S. Geol. Surv., Pt. IV; and topographic maps of Camp Clarke, Brown's Creek, and St. Paul sheets, and the folios of the state, published by the U. S. Geol. Surv.

² Gilbert, Mono. I, U. S. Geol. Surv.

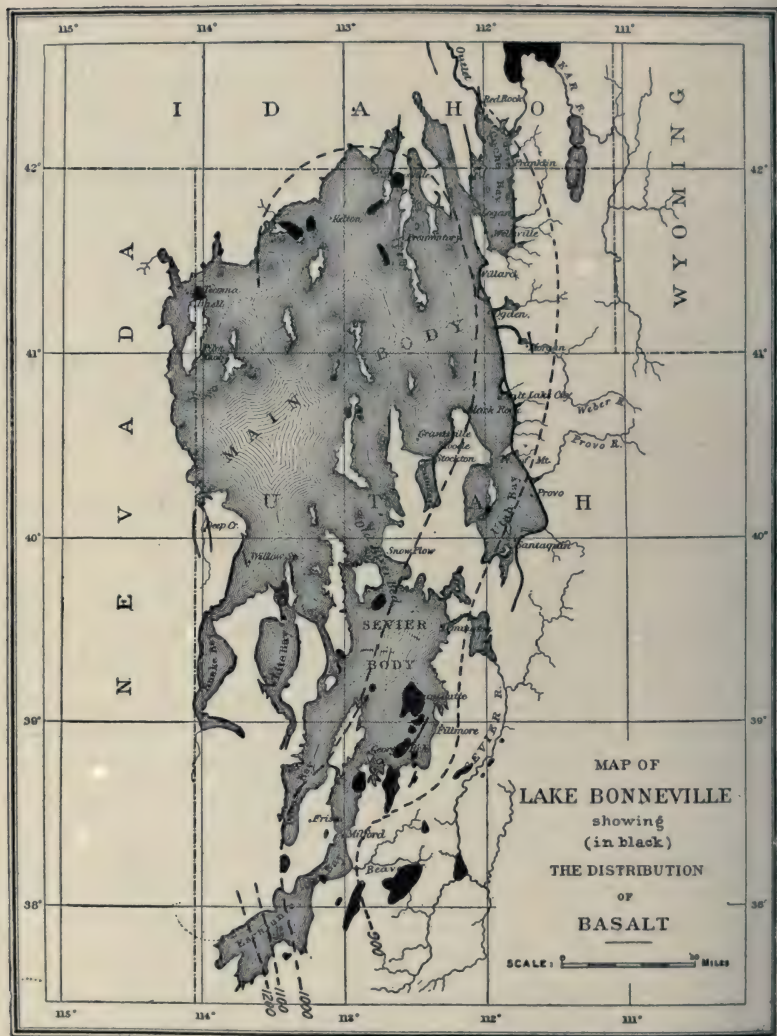


Fig. 596.—Map of Lake Bonneville, showing also the areas of basalt (black areas), some of which are Quaternary, the lines of recent faulting (full black lines), and the deformation of the basin (broken lines). The numbers on the broken lines show the height of the Bonneville shore line above the level of the present Great Salt Lake. (Gilbert, U. S. Geol. Surv.)

into existence, but after a time it appears to have dried up, probably because of another change of climate. Still later, the lake was restored, and its water rose higher than before, and found an outlet to the northward. In the course of time, evaporation from the lake again became more considerable than precipitation and inflow, and the lake gradually shrank to the present dimensions of Great Salt Lake. At its maximum, Lake Bonneville was more than 1000



Fig. 597.—Shore of former Lake Bonneville, Wellsville, Utah. (U. S. Geol. Surv.)

feet deep, and had an area of more than 19,000 square miles; the maximum depth of Great Salt Lake is less than 50 feet (average less than 20) and its area but about one-tenth that of its ancestor. It is apparently doomed to still further decrease by the diversion of water from the feeding streams for purposes of irrigation.

Terraces, deltas, and embankments of other sorts were developed about the shores of Lake Bonneville wherever the appropriate conditions existed (Figs. 269 and 597), and because of the aridity of the climate since the lake sank below them, they have been modified but little by erosion. As the lake dried up, deposits of salts were made, among which sodium chloride and sodium sulphate are most

abundant. Great Salt Lake is estimated to contain 400,000,000 tons of common salt, and 30,000,000 tons of sodium sulphate.

Igneous eruptions (Fig. 596) have taken place within the basin at various stages of the lake's history, even since Lake Bonneville disappeared. Since this time, too, there has been faulting in the basin (Figs. 598 and 599), with displacements of as much as 40 feet. Furthermore, the shore lines of the former lake have been deformed



Fig. 598.— Faulting on the shore of Lake Bonneville (Church).

so that some parts of the Bonneville shore line are more than 300 feet higher than others (Fig. 596).

Farther west, but still in the area of the Great Basin, were other lakes, probably contemporaneous with Bonneville. Among them Lake Lahontan¹ was of importance. Its history and that of a lake which occupied a part of Mono Valley, California,² were similar to that of Lake Bonneville.

Glacial effects. The extent of glaciation in the western mountains has been outlined in the early part of this chapter. The erosive work of the mountain glaciers was considerable, as shown both by the extensive deposits of glacial drift, and by the forms of the valleys which the glaciers occupied. The most massive accumu-

¹ Russell, Mono. XI, U. S. Geol. Surv.

² Eighth Ann. Rept., U. S. Geol. Surv.

lations of drift are in the form of lateral moraines which in some cases are nearly or quite 1,000 feet high.¹ Under the conditions of active drainage which existed in the mountains, much of the glacial debris was carried beyond the ice by the water emanating from it, and deposited in the valleys and "parks," or on the plains below. Glacial cirques, the result of a peculiar phase of glacier erosion, are well developed in many of the glaciated valleys, as for example, in the Uinta Mountains.²

The characteristics of mountain valleys which were occupied by considerable glaciers, are essentially constant. They include (1) well developed cirques at the heads (Pl. XVII); (2) the upper parts of the valleys were so thoroughly cleaned out by the ice that



Fig. 599.— Fault scarps in the moraine at the mouth of the Little Cottonwood Canyon, Wasatch Mountains. (Gilbert, U. S. Geol. Surv.)

little loose debris, except that due to post-glacial weathering, remains; (3) numerous tributary valleys are hanging (Fig. 209), and their waters form cataracts; (4) at and near the limits of the ice, at stages when its end or edges remained nearly constant in position for a time, there are heavy accumulations of drift, lateral moraines being as a rule more conspicuous than terminal; (5) the valleys contain lakes (Pl. XVII), some of which occupy rock basins, and some basins produced by drift dams; and (6) valley trains or outwash plains below the moraines. The partial removal of these deposits has developed terraces (Fig. 163).

Glacial lake deposits. By obstructing valleys, the mountain glaciers of the west gave rise to numerous temporary lakes in which lacustrine sediments were laid down. The extent of such lakes in the west and northwest has not been determined, but where glacia-

¹ This means that the drift is 1,000 feet deep. The crests of the lateral moraines are locally 2,500 feet above the valley bottoms. See Cloud Peak, Wyo., folio, U. S. Geol. Surv. and Professional Paper 62 (Atwood).

² See Hayden Peak and Gilbert Peak, Utah, topographic sheets of the U. S. Geol. Surv., for fine examples of large cirques.

tion was extensive, derangement of the drainage was common, and deposits of glacio-lacustrine clay, hundreds of feet deep, are known at some points. Where such deposits were made in narrow valleys now drained, they have been partly removed, and their remnants constitute terraces.

Alluvial and talus deposits. In the basin region of Utah and Nevada, there are exceptional deposits of detritus, the accumulation of which was favored by topography and climate. The mountain ranges of the basin region are separated by broad depressions. From the steep slopes, detritus is carried down both by descending torrents and by gravity, and while it is largely deposited at and against the bases of the mountains, some of it is spread widely over the surrounding plains. This debris is mainly unstratified, or poorly stratified, and some of it is very coarse. It occurs in greatest quantity where canyons issue from the mountains, and in such situations huge fans of boulders, sometimes 1,000 feet in height, are found.¹ The torrents were able to carry this coarse material so long as they were confined within the canyons, but with the change of gradient below, the water gave up its load. As the glacial deposits increase in importance to the north, talus and other sub-aërial accumulations become less conspicuous, and are of much less importance in Montana, Idaho, and Washington, than in the more arid and unglaciated regions farther south.

Eolian deposits. The wind is an important agent of erosion and deposition in the west. Its erosive work is shown in the peculiar carving which affects the cliffs and projections of rock at many points (Fig. 62), and its depositional work by the dunes, which are not rare. The erosive work of the wind here is far greater than is commonly appreciated by those unfamiliar with arid regions.

Deposition from solution. About many springs, as in the Yellowstone Park, deposits of siliceous sinter and calcareous tufa are now making (Fig. 175). Considerable deposits of a similar nature antedate the present by a notable interval of time, but probably fall within the limits of the Quaternary period.

Marine deposits. At some points along the western coast of the United States marine deposits reach inland some distance from

¹ King, Geol. Surv. of 40th Parallel, Vol. I.

the sea. They reach altitudes of 200 or 300 feet in California¹ and Oregon, and perhaps even higher. The submergence indicated by the position of these beds must have given origin to considerable bays in the lower courses of the Columbia and Willamette valleys. By far the larger part of the marine Quaternary deposits of the coasts of the continent are still beneath the sea.

Igneous rocks. The Quaternary eruptions of North America have not been clearly separated from those of the late Tertiary, but there are some igneous rocks which are Quaternary, some of them even late Quaternary. Mount Shasta shows several post-glacial lava-flows,² and there are small cinder cones on alluvial cones at the east base of the Sierras in southeastern California. In southern California (Mohave desert) and northern Arizona (vicinity of Flagstaff) there are cinder cones, and lava-flows of limited extent which are so slightly touched by erosion that there can be little doubt that they date from a time long subsequent to the beginning of the Quaternary period. Judged by the same criteria, there are lava-flows and cinder cones of Quaternary age in New Mexico, Colorado, Utah, Nevada, Oregon, (p. 382), Idaho,³ Washington,⁴ and at various points in the Sierras.⁵ On many of them vegetation has hardly begun to gain a foothold. Gilbert estimates that of 250 lava-fields observed in these states, 15% are of Pleistocene age, and of 350 volcanic cones in the same states, 60% are considered to be Pleistocene.⁶ Volcanic ash is interbedded with loess at various points in eastern Washington and Oregon,⁷ and overlies glacial moraines in some parts of Alaska.

CHANGES OF LEVEL DURING THE PLEISTOCENE

The very considerable changes of level which marked the closing stages of the Pliocene have been mentioned, and many of them

¹ Ashley, *Jour. Geol.*, Vol. III, pp. 446-450.

² Diller, *Physiography of the United States*, pp. 245 et seq.

³ Nampa, Ida., folio, U. S. Geol. Surv.; also Russell, Bull. 217, U. S. Geol. Surv.

⁴ Tacoma and Ellensburg, Wash., folios, U. S. Geol. Surv.

⁵ See Bidwell Bar, Colfax, Downieville, Lassen Peak, Pyramid Peak, and Truckee, Cal., folios, U. S. Geol. Surv.

⁶ Mono. I, U. S. Geol. Surv., pp. 323-337.

⁷ *Jour. Geol.*, Vol. IX, p. 730.

doubtless continued into the Pleistocene. Minor movements of later date, such as those which affected the basins of Lakes Bonneville and Lahontan during the Pleistocene have also been noted, but such changes are probably but a meager index of the crustal warpings of the period. Specific data on this point are less abundant than could be desired, for the phenomena of erosion and deposition which followed the elevation of the Ozarkian or Sierran epoch are not readily differentiated from the similar phenomena resulting from later elevation. Nevertheless evidence of Pleistocene changes of level, as distinct from late Pliocene, are not wanting, especially near the coasts and about the shores of the Great Lakes.

From the evidence at hand, it appears that deformative movements were wide-spread both in the western mountains and in the area covered by the great ice-sheets. In general, the areas covered by the ice-sheets have risen since the ice melted. It is a tenable hypothesis that the rise, or some part of it, resulted from the melting of the ice, and that it followed a depression caused by the weight of the ice. The rise of the land has on the average been greatest where the ice was thickest.¹ This rise of the glacial centers is shown in various ways, but especially by the raised beaches along the coasts, and by the deformed shore lines of the interior lakes. Thus the shore lines of Lake Agassiz² are considerably higher at the north than at the south, their inclination being as much as a foot to the mile in the northern part of the basin. The shore lines of Lake Iroquois³ (p. 883) decline from the northeast to the southwest at the average rate of three and a half feet per mile. East of the east end of Lake Ontario they are about 400 feet higher than at the west end. The beaches of Lake Algonquin⁴ (Fig. 588) are 25 feet above the present lake at Port Huron, and 635 feet above the lake at North Bay, Ontario. The shore lines of the other lakes show comparable warping.

There have been changes of level, though less extensive in most places, in regions which were not glaciated. Thus along the

¹ DeGeer, Proc. Boston Soc. Nat. Hist., Vol. XXV, 1892.

² Upham, Mono. XXV, U. S. Geol. Surv.

³ Gilbert, 18th Ann. Rept., U. S. Geol. Surv.

⁴ Taylor, A Short History of the Great Lakes, published in *Studies in Indiana Geography*; also Am. Jour. Sci., Vol. LXIX (1895), pp. 69, 249.

Atlantic coast south of the drift there have perhaps been complex movements, but of no great range, in the course of the period. On the whole, elevation (relative) appears to have exceeded depression, but the latest movement (present) appears to have been one of sinking, as the drowned ends of the valleys show.

It is not improbable that movements of equal magnitude have affected the interior regions of the continent, but except about the lakes, there is no datum plane like the sea-level to which these changes may be readily referred. In a few places, notable local deformation is known. In western New York¹ and Ohio, the solution of underlying gypsum and salt is suspected of being the occasion of some of the slight deformations which have been observed.

Some of the islands of Southern California seem to have risen, relatively, some 1,500 feet since the Pliocene. Other parts of the California coast, and some of the adjacent islands, have been subsiding during the same period.² Near San Francisco, the surface is thought to have ranged from 1,800 feet below its present level, to 400 feet above.³ Along the northwestern coast of Oregon, a rise of at least 200 feet during the Pleistocene⁴ has been estimated.

Foreign

The salient points in the glacial history of Europe have been sketched and some indication has been given of the extent of the deployment of ice in other continents. It need only be added here that outside the areas affected by the ice, there are, in all continents, accumulations of sediment of the sorts just enumerated. In Europe there are cave deposits of Quaternary, perhaps of glacial age, which are of especial interest because they contain human relics, probably the oldest known. The relics consist of rude stone implements, bones of mammals with human markings on them, and bones of human beings.

¹ Gilbert, Proc. Am. Ass. Adv. of Sci., Vol. XL, p. 249.

² Lawson, Bull. Dept. Geol., Univ. of Calif., Vol. I. Reviewed in Jour. Geol., Vol. II, p. 235.

³ Ashley, Jour. Geol., Vol. III, p. 449.

⁴ Diller, 17th Ann. Rept., U. S. Geol. Surv., Pt. I.

THE LIFE OF THE PLEISTOCENE PERIOD

Destructive effects of glaciation. Glaciation was the great physical event of the Pleistocene period, and its effect on the life of the times is the topic of chiefest interest in connection with the life of the period. It is reasonable to believe that the successive ice-sheets, several million square miles in extent, destroyed much life, and caused great change in that which survived. The logic is so cogent that we must believe it to be true; yet so far as the record shows, the difference between the preglacial life and the post-glacial is less than might have been anticipated. Thus more than half the known species of the marine Pliocene invertebrates are still living, whereas, in the transition between several of the more ancient periods, nearly all species disappeared. Of the Pliocene plant species, a very considerable percentage are still living. The land vertebrates, on the other hand, were very generally replaced by new species, and the same appears to have been true of the insects.

At the height of glaciation, the sum total of life on the globe must have been greatly reduced. Even the re-expanded life of to-day is probably inferior, quantitatively, to that of the middle Tertiary. Not only this, but existing life is, on the whole, probably poorly adjusted to its surroundings, for it is improbable that, in the millions of square miles where life was destroyed by the ice, there has yet been worked out the best balance between the vegetation and the soils and climate on which it depends, between the carnivorous animals and the herbivores on which they prey, not to speak of all the complicated minor relations that are involved in a well-adjusted peopling of the earth.

To-and-fro migration. An important biological effect of the ice-sheets on life, was enforced migration in latitude. With every advance of the ice, the whole fauna and flora of the affected region had to move on in front of it, or suffer extinction. The arctic species immediately adjacent to the ice border crowded upon the sub-arctic forms next south of them, the sub-arctic forms crowded upon the cold-temperate, and these in turn upon the warm-temperate and so on. It is not unlikely that the limits of the tropical

zones were somewhat shifted, and the zones themselves narrowed. During the interglacial epochs, migrations were reversed. As the zones were shifted back and forth alternately by the advances and retreats of the ice, every organism was under special stress to adapt itself to a new zone, to migrate, or to die. There appear to have been four to six such to-and-fro migrations in America and Europe, and the swing of these movements was several hundred miles, and in some cases perhaps one to two thousand miles. During some of the interglacial epochs, the life of middle latitudes indicates a climate milder than the present, and hence that the ice-sheets were reduced at least as much as now. During some of the interglacial epochs, northern lands seem to have supported as many plants and animals as now. This carries the conclusion that the migratory swing in these more pronounced cases was some 2,000 miles in North America, and more than 1,000 miles in Europe. As indicated in the physical description, other geological evidence warrants the belief that the interglacial intervals were long enough to permit a complete northern return of the life which was forced south during glacial epochs, and the fossil evidence supports the conclusion that the climates were congenial enough to invite it.

The forced migrations must, in their nature, have been peculiarly effective in causing a severe struggle for existence. Forms previously specialized to meet local conditions were put to a most adverse test, for the invading ice forced every form within the glaciated area to move on, while the fringing zones of depressed temperature encircling each ice-sheet, forced plant and animal life, even beyond the ice border, to seek new fields. An incidental result of this wholesale migration was an unwonted commingling of plants and animals, for every aggressive form pushed forward in the van of the advancing zone, and hence came into new organic environment, while every laggard fell behind, and was overtaken by less reluctant migrants.

Climatic adaptations. It has been remarked before that the floras of the middle Tertiary were mixed, judged by the present distribution. Types which we now regard as tropical lived in high latitudes, with forms which are now boreal. So also species that are now boreal lived in low latitudes then with forms which are now

tropical. The to-and-fro movement of the climatic zones seems to have sorted out the mixed assemblage, or to have forced special types into special adaptations, or both, so that to-day most species are confined to definite climatic zones. Adaptation to climatic zones and restriction to them seem therefore to have been favored by the climatic fluctuations of the glacial period.

Relics of glacial migrations. Significant evidence of the northerly and southerly migrations of the glacial period is found in the existing life of the higher mountains within or near the borders of the once glaciated areas. It is obvious that at the time the ice stood in the vicinity of these mountains, the only life which could occupy them was of the arctic type. As the ice retired to the north, the arctic life of the surrounding lowlands moved northward after it, and the temperate life came on to take its place. In the mountains, however, the arctic life still found congenial conditions, by ascending to higher and higher altitudes as the warmer climates advanced. It was thus cut off from the retreating arctic life of the lowlands, and at length isolated. In the high mountains, such life still finds suitable conditions. In some of the higher parts of the northern Appalachians, plants, insects, and small mammals whose kin now live in the arctic zone, remain to this day. The same point is still more strikingly illustrated in the Alps.

Life of the Interglacial Stages

By far the larger part of the fossils whose exact relations to the ice invasions can be fixed, are found in the interglacial beds. These, therefore, possess the highest order of value.

The Toronto beds. The most instructive interglacial beds carefully studied in America are those on the Don River and in the Scarboro cliffs, near Toronto.¹ The fossil-bearing beds are underlain by a sheet of boulder clay the age of which is not determined, but it is the equivalent of one of the older drift sheets. Its upper surface was eroded before the fossiliferous interglacial beds of stratified sand and clay, with a maximum thickness of more than 150

¹ Coleman, *Interglacial Fossils from the Don Valley, Toronto*, Am. Geol., Vol. XII, 1894, pp. 86-95, with references to earlier literature; also *glacial and Interglacial Beds Near Toronto*, Jour. Geol., Vol. IX, 1901, pp. 285-310.

feet, were deposited upon it. The lower part of the interglacial accumulations constitutes the Don formation, and the upper part, the Scarboro formation. Subsequent to the erosion of the latter, thick sheets of boulder clay and assorted drift of Wisconsin age were deposited upon it.

The Don formation contains a warm-temperate fauna and flora, and the Scarboro formation a cold-temperate fauna and flora above. Up to 1900, the flora of the warm-temperate stage had yielded 38 species of plants, many of which indicate a climate appreciably warmer (3° to 5°) than that of Toronto at present. Among these are the pawpaw and the osage orange, which now flourish only in more southerly latitudes. The fauna includes about 40 species of mollusks, some of which are now living in Lake Ontario, some in Lake Erie, while some are not known in the St. Lawrence waters.

The flora of the Scarboro beds embraces 14 species of plants, and the fauna 78 species of animals, 72 of which are beetles. This assemblage implies a climate of about the type which now prevails in southern Labrador. The arctic fauna and flora which should theoretically have followed this cold-temperate one, heralding the approach of the next ice-sheet, are undiscovered.

Other interglacial epochs. In other interglacial formations, there is evidence at many points of an ample growth of vegetation, recorded in peat and muck beds, in humus-bearing soils, and in twigs, limbs, trunks, etc., of trees. From these no great number of species has been identified. Recently, bones of horses (more than one species) have been found in the Aftonian interglacial beds in Iowa,¹ along with bones of elephants and mastodons.

Marine Life

On the more northerly coasts. During that stage of the Wisconsin glaciation when the eskers of Maine were being formed, and the sea-level stood higher than now relative to the land along that part of the coast, arctic mollusks abounded in the shore-waters and were buried in marine clays formed contemporaneously with the eskers.² The species live now in waters that are near the freez-

¹ Calvin, G. S. A., 1908.

² Stone, Mon., U. S. Geol. Surv., XXXIV, 1899, pp. 53-54, and Bastin, Rockland, Me. folio, U. S. Geol. Surv.

ing point most of the year. Remains of walruses, seals, and whales also have been found. In the Champlain substage, the arm of the sea that occupied the lower St. Lawrence and Champlain valleys was peopled by a marine fauna of the same type, essentially, as that which now lives about the mouth of the St. Lawrence and on the coast of Labrador.

On the more southerly coasts. Away from the immediate influences of the ice-sheets, the record of marine life does not indicate any profound departure from the progressive modernization that had been in progress through the Tertiary period. It has been stated by Dall that the Pleistocene fauna of the Atlantic coast does not imply as cold waters as the Oligocene fauna does, and by Arnold that the Pleistocene fauna of the California coast does not imply as cool a climate as the Pliocene fauna of that coast. It is to be noted, however, that the known marine record may not cover more than a small part of the Pleistocene period, and that it is not certain, — perhaps not probable, — that the portion represented was one of the glacial epochs. When the ice was pushing into the ocean on the coast of Maine, as in the late Wisconsin epoch, and an arctic fauna occupied that coast, it is scarcely probable that a warm-temperate fauna lived on the southern coast; nor is it probable that, when icebergs were being set free into Puget Sound, and along all the coast to the north, a warm-temperate fauna lived on the California coast; but warm-temperate faunas on those coasts during interglacial epochs are entirely consistent with a climate such as that suggested by the Don beds.

The Terrestrial Life of the Non-glacial Regions

The life of the lands distant from the glaciated areas cannot now be correlated closely with the glacial and interglacial stages. One of its features was northerly types which appear to have been driven south by the advancing ice, and, later, to have followed its retreating edge northward. The mammoth and mastodon, the bear, bison, reindeer, and musk-ox, were characteristic members of this group. In mid-latitudes, there were several types on the verge of extinction in North America, such as the horse, tapir, llama, and sabre-tooth cat. It is not improbable that there was

intermigration with Eurasia by the northeastern or northwestern routes during the interglacial intervals. A second prominent feature of the faunas was a southern group consisting of gigantic sloths, armadillos, and water-hogs, whose forebears had come from



Fig. 600.— An interpretation of *Mastodon americanus* by G. M. Gleeson.
(From painting in National Museum, Washington.)

South America a little earlier when the isthmian route was open to land animals.

The boreal group. As in the Pliocene, the proboscideans dominated the fields and forests of mid-latitudes. The mammoth ranged from Mexico northward, reaching Canada and Alaska at times of maximum deglaciation. In Siberia, the mammoth was covered with wool and hair, and was obviously adapted to a cold climate. The mammoth survived the glacial period in America, and its tusks and skeletons are not infrequently found in beds of peat and muck that have accumulated since, in northern United States and Canada. The mastodon also ranged northward into

Canada, but since it emigrated to South America and crossed the tropics, it cannot have been ill-adapted to a warm climate. It likewise outlived the glacial period. Williston suggests that while mammoths were abundant in Kansas and on plains where forests did not prevail, mastodons were mostly confined to valleys and timbered regions, notably those of the eastern States, the eastern part of the Mississippi basin, and the Pacific coast.

Several species of horses have been found in western beds referred to the Pleistocene period. A gigantic elk ranged from Mississippi to New York. Two or three species of buffaloes roamed over the Ohio valley and southward to the Gulf, and remains of the musk-ox and reindeer, distinctively arctic animals, have been found as far south as Virginia and Kentucky. Bears, rather recent emigrants from Eurasia, were present, as were wolves and peccaries.

The southern group. Over against this assemblage of more or less boreal forms pushed southward by glacial advances, there was the group of South American immigrants, the monster sloths, *Megatherium*, *Myiodon*, *Megalonyx*, and the gigantic armadillo *Glyptodon* with a strong carapace and a massive tail plated with spiked ossicles (Fig. 601). The remains of this group have been found chiefly in caverns and crevices, or in the muck and mire about salt springs, or in fluvial deposits, the precise ages of which are difficult to fix. There is apparently nothing in the climatic conditions of such an interglacial stage as that which permitted paw-paws and osage oranges to flourish about Toronto, to forbid the presence of these animals in the most northerly ranges in which their relics are found, Pennsylvania and Oregon.

Pleistocene Life in Eurasia

The changes undergone by the life in Europe, during the glacial period, were similar to those already sketched for America.

During the first glacial epoch, a thoroughly arctic fauna lived in the North Sea, while during the first recognized interglacial epoch, the arctic fauna retreated northward. During this interglacial interval, a temperate flora, comparable to that now living in England, clothed the British Isles, while the hippopotamus, elephant, deer, and other mammals invaded Britain by way of the

land bridge which then connected it with the continent. A similar flora and fauna advanced to corresponding latitudes on the main land. A luxurious deciduous flora occupied the valleys of the Alps, and flourished at heights which it no longer attains. Toward the close of this interglacial epoch, the temperate flora gave place to an arctic flora.

During the second glacial epoch, according to Geikie,¹ the ice reached its maximum extent in Europe, and arctic-alpine plants

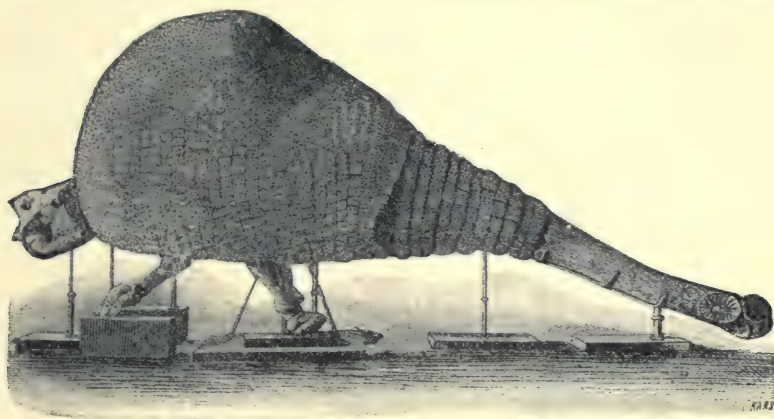


Fig. 601.—A club-tailed glyptodont, *Dedicurus clavicaudatus*, from South America. (Lydekker.)

occupied the low grounds of central Europe, while northern mammals, including the reindeer, the arctic fox, etc., reached the mountains of southern Europe, and even the shores of the Mediterranean.

During the second interglacial epoch, the arctic-alpine flora and the northern fauna of central Europe were replaced by a temperate flora and fauna. The plants which then occupied northern Germany and central Russia imply a climate milder than the present, and the mammalian fauna, which included the hippopotamus and elephant (*Elephas antiquus*), was in keeping with the flora. Toward the close of this interglacial epoch, however, a northern facies began to be assumed, and as the third glacial epoch came

¹ The Great Ice Age, Third Edition, pp. 607-615.

on, the northern types were pressed well to the south, though not so far as in the preceding epoch. In the third interglacial epoch the mammalian fauna included the Irish deer, the horse, the mammoth, and the woolly rhinoceros. The climate seems to have been congenial to a cool-temperate fauna.

During the remaining epochs, the oscillations were apparently less, and the to-and-fro migrations of life appear to have become less and less, corresponding to the diminishing oscillations of the glacial stages.

Pleistocene life of other continents. The Pleistocene life of North America and Europe were similar, but that of *South America* had a character quite its own. The major fauna was composed of two great elements, (1) the gigantic sloths and armadillos, which were indigenous to that country and very numerous, and (2) the descendants of the Pliocene mammals which had migrated from North America. Among the northern immigrants were horses, mastodons, llamas, tapirs, wolves, and a large variety of rodents.

Owing to the isolation of *Australia*, its organic development followed lines of its own. The vertebrate fauna consisted exclusively of marsupials and monotremes. In general, they differed, specifically, from those now living, and were, on the whole, larger. Although glaciers had but slight development in Australia, the effects of the wide-spread refrigeration of the higher latitudes was doubtless felt.

Comparatively little is known of the Pleistocene life of *Africa*. A moderate climate in the northern portion seems to be attested by fluvial accumulations which have yielded remains of the buffalo, antelope, hippopotamus, rhinoceros, and horse. These appear to have belonged to an early stage of the Pleistocene. A later stage is represented by mollusks of existing species, and a mammalian fauna embracing the elephant, buffalo, hippopotamus, antelope, sheep, camel, and horse, a group differing widely from the present occupants of the region.

Man in the Glacial Period

In America. Previous to the last decade of the last century, no small mass of prehistoric material of human origin had been

assembled and somewhat widely accepted as conclusive of man's presence in America in glacial times. The rise of a more critical spirit in archæologic geology, and the application of more rigorous criteria have, however, disclosed weaknesses both in the evidence and in the interpretations put upon it, with the result that man's antiquity in America is a more open question to-day than it was thought to be fifteen years ago.

Prehistoric human relics in America range from the rudest stone chippings and flakings to skillfully fashioned and often polished handiwork in stone, metal, and bone. Following European precedent, the earlier students in America classed the rougher artefacts¹ as *paleolithic*, and interpreted them as indicating the presence of Paleolithic man, and of the Paleolithic or Old Stone age in America. The more perfectly fashioned artefacts were classed as *neolithic*, with corresponding reference to the Neolithic or New Stone age. Some investigators very properly regard "paleolithic" and "neolithic" merely as stages of early art, and not as chronological "ages," or geologic divisions, but the terms have been much used in the latter sense.

The relics interpreted as paleoliths consist chiefly of rudely chipped pieces of flint, quartz, argillite, etc. (Fig. 602). With them other products of early art are found. The neoliths embrace a wider range of stone artefacts, typified by well-chipped arrow-points, spear-heads, knives, and scrapers of flint or quartz, and by the ground and polished axes, chisels, pestles, mortars, and other implements of greenstone and similar tough or workable rock. The paleoliths, as defined above, were confidently interpreted as the work of an earlier and less cultured people, while the neoliths



Fig. 602.— A typical paleolith from Kent's Cavern, Torquay, England, seen on the face and edge. (Evans.)

¹ The term "artefac" designates any object fashioned by man, in any way or for any purpose, or, incidentally, without purpose. It includes stone chips, broken and rejected material, and various forms of by-products, as well as implements, weapons, ornaments, etc.

were known to have been the customary implements and weapons of the natives of the continent when first invaded by Europeans. Stone axes have been found in abundance in the ancient copper mines of the Lake Superior region, and thus the use of stone and of copper implements is shown to have been contemporaneous; but this was long after the retreat of the last ice-sheet. It is to be noted that the phase of the stone art designated neolithic was dominant on the continent until recent times, and is scarcely yet extinct, and that it was contemporaneous with the "Iron age" of Europe, entirely overlapping the "Bronze age."

The chief points brought into question by the critical inquiries of recent years are (1) the reference of the ruder artefacts to a stage of art more primitive than that of the Indians and other aborigines, and (2) the reference of the gravels and other superficial formations in which they were found to the glacial period.

By a series of investigations relative to the first of the points, Holmes¹ reached the conclusion that the early inhabitants of the country, like the later Indians, resorted habitually to gravel-beds and to outcrops of appropriate rock to procure the raw material for their stone artefacts, and that it was their custom to test and to rough-out the material on the ground, leaving the chippings and the rejected material scattered about when the rough work was done. The more delicate work of shaping the rough material into implements was apparently done as need required, at their dwelling sites or other convenient places to which stone from the quarries was carried. A full series of the stages of manufacture, as thus interpreted, is shown in Fig. 603.

By virtue of this separation of the process of manufacture into two parts, (1) roughing out at the quarries, gravel-beds, etc., and (2) shaping tools at dwelling sites or elsewhere, there arose a geographic separation of the products. The rude failures and rejects, together with the extemporized hammer-stones, cores, flakings, and chips, were scattered about the sites of the raw material.

¹ Holmes, W. H., A Stone Implement Workshop, *Am. Anthropologist*, Vol. III, 1890, pp. 1-26; Review of the Evidence Relative to Auriferous Gravel Man in California, *Smith. Rept.* 1900, pp. 417-472; Stone Implements of the Potomac-Chesapeake Tidewater, *Ann. Rept. Bureau of Eth.*, 1893-94, pp. 1-152, and *Jour. Geol.*, Vol. I.

while the completed implements were liable to be found only about the dwelling sites, or wherever, in the course of their use, they were lost or thrown aside. In the light of this definite separation, it is not difficult to see how the idea of two stages of art might arise, and how easily the finds might be misinterpreted.

The most available sites for finding suitable raw material in a convenient form were the river gravels and the terrace formations. This was especially true in and about the glaciated regions where



Fig. 603.— A series of forms illustrating progressive steps in the manufacture of arrow-points from quartz pebbles obtained mainly from shops and village-sites, near Anacostia, D. C. (Holmes.)

trains of glacial gravels led away from the ice-fields. In these, quartz, flint, chert, etc., were usually abundant, in the convenient form of pebbles and cobbles.

The rude artefacts in question have been found chiefly in such gravels, but gravels derived from chert-bearing limestone or quartz-bearing rock are also fruitful sources. In other words, there is a correspondence between the distribution of the ruder artefacts, and that of the raw material. The distribution of the finished artefacts is much wider and more varied. There is special infelicity in supposing that great numbers of implements would be lost in glacial rivers during the glacial epochs, for the waters of these rivers must have been so cold and silty, that they contained little life. Later, when the climate was milder and the streams warmer and clearer,

and when the adjacent country was filled with game and when the glacial gravels were exposed in bluffs and channels, these streams must have afforded abundant material for stone implements.

The demonstration of two stages in the manufacture of arrow-points, spear-heads, knives, etc., as practiced by the aborigines of the country, raised the question whether there are any true paleolithic artefacts in North America. The difficulties of discriminating between "paleoliths" and "rejects," if indeed they can be discriminated, is illustrated by Fig. 604. One of the chipped blades represented has been regarded as a typical "paleolith," while the other forms are "rejects."

It has been found that most of the artefacts in valley gravels are in their superficial portions, in their talus slopes, or in secondary deposits, many of which are of recent origin. Of the less superficial finds, many have been shown to be cases of relatively recent burial by natural means. The processes of streams in cutting down their channels in valley gravels are such that superficial material may be buried to very considerable depths. In their meanderings, they cut into the bordering terraces or uplands, developing steep bluffs. When the meanders shift, as they are sure to do, the bluffs grade down to a slope by the falling, or sliding, or washing of the top to the bottom, as illustrated in Figs. 605-607. The material which was in the top originally, may get into the base of the talus, and be buried deeply. Similar secondary burial takes place in all sorts of loose material of eolian, pluvial, and fluvial origin. It is to be noted that this is a normal process, not an exceptional one. There are other ways, too, notably scour and fill (p. 184), in which human relics may be buried in river gravels.

Without further details, it may be said that human relics have not been found, in America, in gravels known to have been deposited in the glacial period, or before. All that have been reported from glacial gravels, have been found either in such positions as to show that they were buried in post-glacial time, or in such positions as to make this inference tenable. The existence of man in America in the glacial period or before is therefore not demonstrated.

Sources of good evidence. There are two classes of formations in which good evidences of glacial man, if there was such man in

America, are to be sought, viz., (1) in undisturbed till-sheets below horizons affected by surface intrusion, and (2) in interglacial beds, where overlain by till and protected from all assignable sources

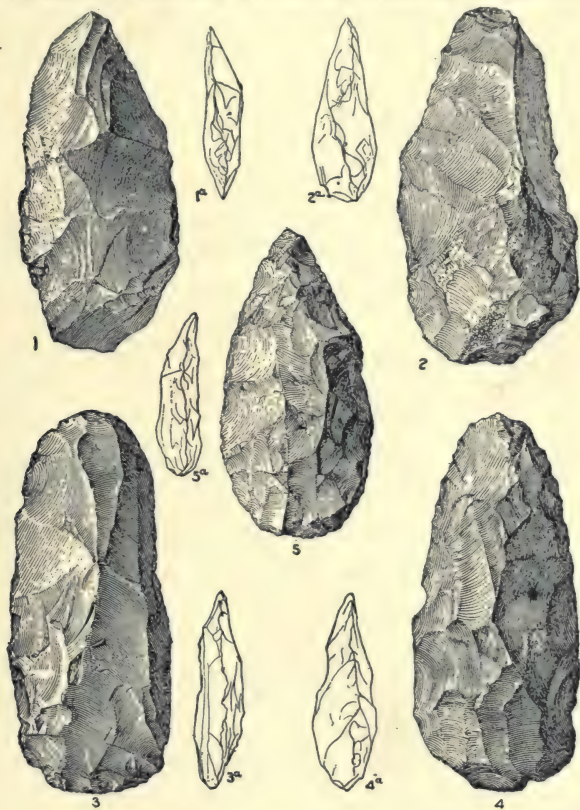


Fig. 604.—A group of figures of chipped-stone artefacts, one of which has been regarded as a typical paleolithic implement, front and side view, while the rest were obtained, in three cases, from modern flint-shops of the region in which the supposed paleolith was found, while the fourth was traceable directly to the same shops. The discrimination between the paleolith and the rejects is left to the reader. (Holmes.)

of subsequent intermixture. Both these classes of beds have yielded fossils of other forms of life, and these alone have been seriously considered in the usual studies of the life of the glacial and interglacial stages. These beds have not yet yielded human

relics in America, but they should do so in time, if man lived here in glacial or interglacial times.

In Europe. The European data indicating great antiquity of man are superior to the American. In Europe there are numerous caves in which the relics of man, mingled with those of extinct

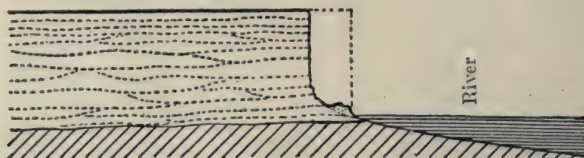


Fig. 605.— A gravel bluff formed by the under-cutting of the adjacent river.
(After Holmes.)

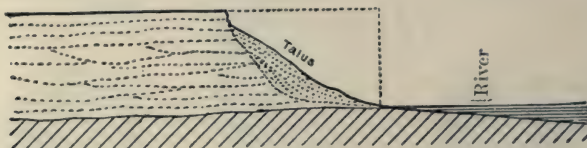


Fig. 606.— The same at an early stage of talus formation.

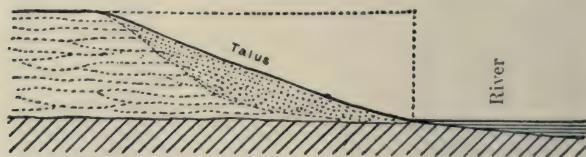


Fig. 607.— The same at a late stage, when the slope has become nearly stable.

animals, have been securely protected by layers of stalagmite. While the ages of the stalagmite layers have rarely been fixed with certainty, or well correlated with the glacial stages, they bear inherent evidence of considerable antiquity. The European cave evidence seems to have no strict counterpart in America.

The association of man with extinct animals is a phenomenon that may mean the extension of man's presence backward, or the extension of the animals' presence forward; and to this double-faced problem research has not yet furnished a final key. Obviously,

however, the larger the number of animal types not known to have lived this side the last glacial stage whose remains are commingled with human relics, the stronger the presumption of man's presence before the close of the glacial period. From this point of view, the European case seems to be strong.

There is one further feature in the European case that is, at least, suggestive. Two climatic groups of animals are associated with the human relics,—a subarctic and a subtropical. In the subarctic group, there were reindeers, mammoths, woolly rhinoceroses, arctic gluttons, musk-oxen, and other boreal forms; in the subtropical group, lions, leopards, hippopotamuses, hyenas, southern rhinoceroses, and other African types. These contrasted groups, as interpreted by James Geikie and others, imply migrations of the kind already sketched as characteristic of the glacial period. While it cannot be positively affirmed that there have been no climatic oscillations of a similar kind since the last glacial epoch, there is a somewhat strong presumption that those implied by these two classes of animals were connected with climatic oscillations of the glacial period. This presumption therefore connects man with at least the later of the glacial epochs.

The relics thus associated with extinct animals have been assigned to paleolithic man, and to a primitive stage of culture. This interpretation is based on the crudeness of the stone artefacts rather than upon the evidence of a higher order of art which the record presents. If, however, the rude stone artefacts are susceptible of being interpreted as the waste incidental to the making of good stone implements,—an interpretation which does not seem to have been yet fully adjudicated in Europe,—a more favorable judgment of the art of these ancient peoples would be reached; for associated with the ruder artefacts (or paleoliths), there are implements of bone, such as needles, awls, harpoons or spears with barbs, etc., implying some advance in art; there are carvings that show not a little skill, and drawings in which the elements of perspective and shading, as well as skill in delineation, are indicated (Fig. 608). These seem to imply a higher stage of art development than is consistent with the exclusive use of paleolithic stone implements. On the whole, present evidence seems to justify the conclusion of most

European archæological geologists, that man was present in southern and central Europe during the later part of the glacial period, and

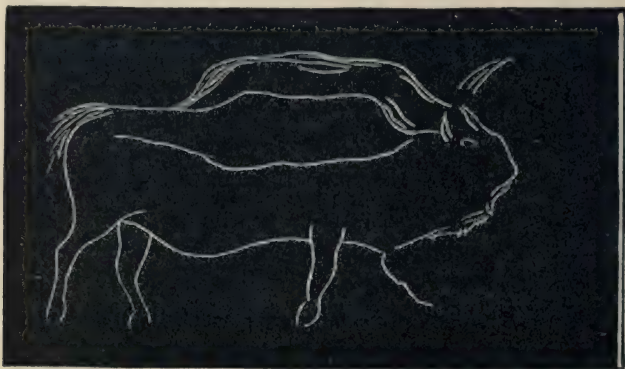


Fig. 608.— Etching of an aurochs on a slab of slate, from the bone cave of Les Eyzies, Dordogne, France, ($\frac{1}{2}$ size). This sketch may be instructively compared with the similar work of the ancient Assyrians and Egyptians. (Prestwick.)

perhaps even early in the period. Penck¹ would place his beginning as far back as the interglacial epoch which, he thinks, may correspond with the North American Yarmouth (p. 874).

References relative to the antiquity of man: Abbott, C. C., Peabody Acad. Sci., Salem, 1881; Proc. Bost. Soc. Nat. Hist., Vol. XXII, 1884; and Vol. XXIII, Smiths. Rept., 1875, and Pop. Sci. Monthly, 1889; Babbitt, F. E., Am. Nat., Vol. XVIII, 1884; Becker, G. F., Bull. Geol. Soc. of Am., Vol. II; Blake, W. P., Jour. Geol., Vol. VIII, 1899; Chamberlin, T. C., Jour. Geol., Vol. X; Geikie, James, The Great Ice Age, pp. 616–690; and Prehistoric Europe, pp. 568 et seq.; Gilbert, G. K., Sci. Am. Supp., Vol. XXIII, 1887; Lyell, Sir Charles, Antiquity of Man; McGee, W. J., Am. Geol., Vol. XXII, pp. 96–126; Sci., new ser., Vol. IX, pp. 104–105; Salisbury, R. D., Sci., new ser., Vol. VI, pp. 977–981, 1897; Upham, Warren, Science, Vol. XVI, pp. 355–6; Am. Geol., Vols. XXX and XXXI; Whitney, J. D., Cal. Proc. Acad. of Sci., Vol. III, pp. 277–278; Am. Jour. Sci., 2d ser., Vol. 43, pp. 265–267, 1867; The Auriferous Gravels of the Sierra Nevada of California, Cambridge, 1879; Williston, S. W., Science, new ser., Vol. XVI; Winchell, N. H., Bull. Geol. Soc. of Am., Vol. XIV; Am. Geol., Vols. XXX and XXXI; Wright, G. F., Bull. Essex Inst., Vol. XIII, 1882; Ohio Arch., and Hist. Quart., 1887; *The Ice Age in North America and its Bearings upon the Antiquity of Man*, pp. 506–571; *Man and the Glacial Period*, pp. 243–307; Brit. Assoc. Adv. Sci. Rept. for 1891.

¹ Science, Vol. XXIX, 1909, p. 359.

CHAPTER XXXI

THE HUMAN OR PRESENT PERIOD

The end of the glacial period. The termination of the glacial period is usually placed at the time when the ice-sheets disappeared from the lowlands in the middle latitudes of Europe and North America. Notwithstanding this conventional usage, it is to be noted that the ice-sheets had not then completely disappeared, and have not even now, for about 10% of the recently glaciated area of North America (chiefly in Greenland) is still buried in ice. These relics of the last glacial epoch show that the continent has not yet emerged completely from the glacial period.

Future glaciation. It is not absolutely clear that there may not be another increase of ice before the long series of glacial epochs closes, but the probabilities seem to be much against it. The declining series of oscillations already noted seems to have reached its last term, yet the factors that produce glaciation are too complex to warrant more than a comfortable presumption of future immunity until another great deformation shall have taken place.

The end of the deformation period. It is not wholly clear that the deformative period which began in the late Tertiary, and extended through the Pleistocene, is yet completed. We are accustomed to regard it as essentially passed, notwithstanding some movements still in progress; and, in the main, this position seems to be justified.

The movements of post-glacial times, however, are not to be ignored. The northeastern part of North America has been elevated relatively since the disappearance of the ice (p. 912). This relative rise is perhaps a reaction from the depression due to the weighting and cooling caused by the ice-sheets.

A recent movement in the region of the Great Plains seems to be suggested by certain physiographic features. Extensive tracts

in central Kansas and Nebraska bear an aspect of pronounced topographic youth, suggesting that they have been lying, until recently, near the neutral horizon between erosion and deposition, and have lately been raised on the western side. In the Dakotas, there are broad gradation plains of abandoned river-courses which cross the present valley of the Missouri River. Their present gradients, and their elevation above the present river-bottoms of the region imply a westward elevation. These and collateral phenomena, taken with the remarkable movement of the Keewatin ice-sheet from what is now the lower to what is now the higher side of the plains, seem best satisfied by the view that until about the close of the Glacial Period the western side of the Great Plains was lower than now, relatively, or the eastern side higher. On the western side of the continent there is much evidence of recent movement, some of which appears to have taken place since the close of the Glacial Period, as usually defined. Similar phenomena are found in other continents.

It is not wholly clear, therefore, whether the present is to be regarded as a part of that period of deformation which had its climax in the Pliocene, of whether it is rather the initial stage of a period of quiescence now being entered upon.

The suggestions of existing physiography. The view that the earth is now passing into a period of quiescence is strengthened by the present physiographic features of the earth's surface. These are an inheritance from the Tertiary deformations superposed upon pre-existing configurations, though they have been modified by gradational agencies since. They should tell us whether the face of the earth is that of a planet in the midst of deformation, or that of one recently deformed, and now in a more quiescent state. Every stream should show whether it has just been rejuvenated, or has done some notable work since it was rejuvenated. Every coast should show whether the continental border stands forth in the manner characteristic of an earth-segment just crowded up by a deformative thrust, or whether it has made some notable progress in settling back, or in being cut back, to an inter-deformative state.

Most of the streams of the continents show that they have had time to do some appreciable work since they were rejuvenated.

Falls which owe their origin to the deformations of the recent deformative period abound on all the continents, but most of them have canyons below, showing that the falls have been receding for a long time. The falls and canyons are often so related to slack water below as to show that the rejuvenating process stopped some time ago. The Falls of the Columbia, Congo, Zambesi, Brahmaputra, Yang-tse, and of a multitude of other rivers descending from the elevated portions of the continents, are illustrations in point. If the various criteria of topographic age are applied to the face of the continents, it will be seen that, while they betray, very generally, evidences of rejuvenation by deformation in relatively recent times, there is very little to indicate rejuvenation now in progress. The most declared evidences of topographic youth are in regions recently abandoned by the ice-sheets of the last glacial stage.¹

If attention is turned to the borders of the continents, significant evidence is found in the fact that the real edges of the continents are almost everywhere submerged. They generally lie 100 fathoms or so below sea-level; that is, continental shelves almost universally border the continents. An area of 10,000,000 square miles, more than 15% of the true continental surface, is thus submerged. The submergence of the shelves took place so recently that they are marked by trenches, valleys, and embayments referable to rivers that formerly crossed them. These features imply that the continental shelves were out of water recently, and that rivers then reached the true borders of the continental platforms. They also imply a recent (if not present) general movement toward continental submersion.

The channels on the continental borders. The conclusion has generally been that the coastal tracts affected by valleys once stood high enough to allow streams to excavate the valleys. As commonly interpreted, this means that the tracts have in recent times stood some thousands of feet higher than now, and the submerged valleys have been much appealed to in support of the elevation hypothesis of glaciation. The submerged valleys of the continental

¹ Jour. Geol., Vol. XII, p. 707.

shelves have occasioned much discussion.¹ To the view that the continental borders stood so high in recent times there are obvious objections. One of them is the difficulty of disposing of the water of the ocean when all the continents were lifted some thousands of feet. Another is the fact that some of these valleys descend into *closed basins* such as the deeper parts of the Mediterranean and Caribbean seas and the Gulf of Mexico, which must be supposed to have retained so much of their water as lies below the lowest notch in their rims.

The views of deformation here entertained afford a different mode of interpretation, in which lateral movement plays a larger part, and vertical movement a lesser part. This view cannot be elaborated here, but some of its elements may be suggested.

It is conceived that the continental protuberances, which stand up some three miles, on the average, above the sea-bottom, may have a movement somewhat akin to that of great ice-sheets, though much slower, and that they tend to creep slowly out toward the lower ocean basins. If such a movement took place, it would tend to carry the valleys of the coastal lands out under the sea. It is conceivable that the submerged valleys arose in this way. This conception of the behavior of continental borders is too new to be accepted without reserve, but if it is true, it helps to explain many difficult problems connected with the coasts.²

However the submerged valleys originated, it seems remarkable that they have not been filled with sediment, for the rivers must have been carrying detritus, and littoral currents must have swept drift into the channels. The efficient agent in keeping the valleys unfilled was possibly the tides. Their ebb and flow, particularly where the river-mouth broadened to an estuary, doubtless scoured the channel, and not improbably enlarged and deepened it where the configuration of the surroundings favored. Tides would seem to be especially effective in this work at the edge of the continental

¹ Spencer, Bull. Geol. Soc. Am., Vols. VI (pp. 103-140) and XIV (pp. 207-226); Am. Jour. Sci., Vol. XIX, 1905, pp. 1-15; and Am. Geol. XXIV, 1904, pp. 110-111; Hall, Trans. Victoria Inst., 1897 (pp. 305-324); and 1900 and 1902, and Geog. Jour., 1899; Nansen, Rep. Arc. Expl., p. 232; Davidson, Proc. Cal. Acad. Sci., Vol. I, 1897, pp. 73-103.

² For fuller statement of the hypothesis see the larger treatise of the authors, Vol. III, pp. 519-530.

shelves. It seems not improbable that valleys in the outer edge of the continental shelf, and on the abysmal slope, are even deepened and widened by tidal scour.

THE LIFE OF THE HUMAN PERIOD

In the seas, and on the land in the tropics, the life of the Pleistocene period appears to have passed by imperceptible gradations into that of the present. In the higher latitudes, the transition was marked by two exceptional features, the re-peopling of the lands laid waste by the ice-incursions, and the invasion of the human race. Whatever may have been true in the low latitudes where the human race perhaps came into ascendancy gradually, the appearance of man in the higher latitudes was an invasion, and from the point of view of other organisms, it was an irresistible inundation.

The re-peopling of the glaciated areas. The re-peopling of the northeastern half of North America by plants and animals after the retreat of the last ice-sheet was a great event of its kind. Certain plants that abounded in Europe before the glacial period were forced across the Mediterranean, or southeastward into Asia, and did not recross the barriers of water and desert when the climate of Europe became mild again. No such barrier intervened in North America, so that the problem of re-peopling can be studied to better advantage in our continent than in Europe. There was, however, an ill-defined climatic barrier between the arid plain region of the southwest and the humid forest region of the southeast. There is abundant evidence that open plains and arid climates had developed in the middle latitudes of the west by the later part of the Tertiary, and that these have persisted, perhaps with brief interruptions, till now. The pre-glacial arid tracts seem to have had a distribution in the western part of our continent not unlike that of to-day, while the eastern half of the continent was then, as now, more moist, and covered with forests rather than herbaceous vegetation.

With the oncoming of the ice-sheets, the floras and faunas were driven southward, as described in the history of that period.

In the west, the northern life was driven by ice behind, hemmed in by mountain and other barriers at the sides, and resisted by arid tracts in front. The arid tracts were themselves shifted in some measure, but the restraint of migration to the east and west became increasingly formidable as glaciers gathered on the mountain heights and occupied the passes. As the trend of the mountains was mainly north and south, they defined a series of meridional tracts which directed the life migrations. Even east of the mountains, climatic differences seem to have appreciably restrained east-west migration.

In the eastern half of the continent, the forests and forest-life were driven southward in a more unrestrained way, but for the greater part they kept within the eastern humid tract.

Following the last ice-retreat, the life of each of these sections moved northward, each biotic zone, arctic, subarctic, cold-temperate, and temperate, expanding as it went. It was as though the life-zones were elastic bodies which had been compressed to narrow limits about the edge of the advancing ice, and then recovered their normal breadth by expansion northward as the ice withdrew. The arctic or tundra flora and fauna that had probably been crowded into a narrow zone fringing the ice-sheet, moved northward through about 20° of latitude, and expanded to a breadth of 600 or 700 miles in the northern part of the continent, and occupied the arctic islands where not covered by perennial ice and snow. The zone of this arctic flora and fauna now lies mostly north of 60° . The subarctic zone of stunted conifers moved northward about 12° , and expanded into a zone some 400 to 600 miles wide. The cold-temperate belt of deciduous and evergreen trees moved a less distance, but expanded almost equally, while the warm-temperate flora spread itself over the territory abandoned by the last.

With each of these vegetal zones went the appropriate fauna. The musk-ox, whose remains have been found skirting the glaciated area in Pennsylvania, West Virginia, Ohio, Kentucky, Oklahoma, Missouri, and Iowa,¹ has since retired to the extreme arctic regions. The reindeer, which had a similar distribution about the edge of

¹ Hay's Catalogue of Fossil Vertebrates in North America, Bull. 179, U. S. Geol. Surv., 1902.

the ice, occupies the barrens of the northern border of the continent; while the fur-clothed animals distributed themselves through the three northerly zones, most notably the subarctic zone of the conifers.¹

The westward spread of these floras and faunas of the southeastern regions seems to have been meager. In the west, the southwestern arid and prairie floras and faunas seem to have had the better of the contest with the forest forms, and to have spread eastward in the mid-latitudes at the expense of the southeastern group; at least arboreous vegetation is found appreciably farther west in interglacial deposits than on the present surface. This does not seem to be equally true in the higher latitudes, where the trees of the eastern group are distributed far to the northwest.

The arid and semi-arid floras and faunas of the southwest seem to have pushed the more boreal and arboreous forms to the northward, or forced them to ascend the mountains; but the movement was less sweeping and more complicated than that of the east, because of topographic interference and the effect of the lingering mountain glaciation.

In this re-dispersion of the North American faunas and floras there is a world of suggestive detail of which only a small part has been worked out into clear definition. From the viewpoint of investigation, it is a rich and almost virgin soil, forming the turn-row, as it were, between the more cultivated fields of the geologic and biologic sciences. Among other things, it seems not improbable that studies on the rate of migration of plants to the northward, after the last glaciation, may afford a basis for estimating the length of post-glacial time.

The Dynasty of Man

Human dispersal. As yet there is little geological evidence relative to the place of man's origin, or to the earliest stages of his development. Various considerations connected with his physical nature and his distribution seem to point to the warm zone of the

¹ Some of these and other features are suggestively discussed by C. C. Adams, *The Post-Glacial Dispersal of the North American Biota*, Biol. Bull., Vol. IX, 1905, pp. 53-71.

eastern hemisphere, perhaps southern Asia or northern Africa, as the place of his appearance. There are some grounds for the inference that the earliest developments of those qualities that gave him dominance were associated with the open tracts of the subtropical zone, rather than with the forests of the equatorial belt. Subsequent history, as well as the nature of the case, teach us that extreme desert conditions and excessive heights are prohibitive, that semi-arid conditions of varying and precarious intensities lead to nomadic habits, sparse distribution, and limited social and civic evolution; while well-watered plains and fertile valleys, under congenial skies, invite fixed habitation and the development of stable civil and social institutions. Excessive humidity, dense forests, extreme ruggedness of surface, tend to limitation and repression among primitive peoples. Early in the history of the race, it is presumed that a warm climate was more favorable than a severe one. From these considerations and from historical evidence arises the presumption that the primitive centers of virile evolution and radiation of the race lay somewhere in the open or diversified parts of the warm tract of the largest of the continents. From this, or from some analogous tract in that quarter of the globe, there seem to have been divergent movements to all habitable lands of the earth.

A basal factor in the early evolution of civilization was the productiveness and availability of the soil. The passage from the condition of hunters and fishers, scattered in adjustment to the distribution of game and shifting with its changes, or from that of simple herders in sterile tracts roaming with the changes of pasture, was dependent essentially on agriculture, and was therefore influenced largely by the fertility of the soil and suitable climatic conditions. And so, conversely, among the agencies that have forced the migration of centers of civilization, loss of soil-fertility is one of the more important. In the lower latitudes, the upland soils are usually the residue left by the decomposition of the underlying rocks which has not been removed by surface-wash. With cultivation, wash and wind-drift are accelerated, and unless protective measures are employed, as has not been the case usually, the soils are swept away, and barrenness succeeds productiveness.

There are areas in the Orient, once well settled, where nothing grows except such plants as find a foothold in the crevices of the rock. Soils with sandy subsoils have been washed away, leaving barren wastes, and the sands derived from the denuded subsoil have been driven by the winds over adjacent fertile tracts, and by burial have included them in the common waste. The explanation of much of the former richness and present poverty of Oriental peoples no doubt lies in this simple process. This impoverishment of soil threatens many peoples to-day, and is in process of actual realization.

Glaciated lands are comparatively new fields for civilization, and the soil-factor there has a character quite its own. 1. Near the centers of glacial radiation, the old soils were borne away, and new soils have not always developed in equal amount in their stead. A reduced fertility is the result. The half-decayed rock below was largely worn away, and a long period must ensue before a new soil will have become effective. These areas lie chiefly in high latitudes where other factors do not favor human development. 2. In regions of glacial deposition, which fortunately include the greater and the more southerly parts of the glaciated area, a deep sheet of comminuted rock-material, ready for easy conversion into soil by weathering and organic action, covers great plains, and has a gentle relief that aids in restraining its removal. In the peripheral belt of the glaciated area in North America, for a width of 400 or 500 miles, the subsoil of glacial flour and old soil, glacially mixed, has an average thickness of about 100 feet. A similar statement may be made of a large area in north-central Europe. The average thickness of the residuary soils of unglaciated regions similarly situated is about 5 feet. The twenty-fold provision for permanent fertility thus arising from glaciation seems likely to be a factor of importance in the localization of the basal industry of mankind, and of the phases of civilization that are dependent on it.

With the evolution of the industrial arts, resources which were neglected at first have come to play important parts in the distribution and in the activities of the race, among which are the long and growing lists of mineral resources. Chief among these are the metallic ores, the fossil fuels, the mineral fertilizers, and the struc-

tural and ornamental materials of stone and clay. These now influence man's distribution and activities far more than formerly, and they are quite certain to be more influential still in the future.

The distribution and activities of men have also recently come to be affected by the distribution of rejuvenated streams that arose from the deformations of the late Tertiary periods, and by the stream-diversions of the glacial period, both of which have furnished sources of water-power heretofore neglected in the main. With little doubt, such native sources of power are to play an increasingly large part in human affairs as time goes on and the stored fuels are exhausted.

With the increasing complexity of human activities, the localization of the race will more and more depend on *combinations of resources and of conditions*; but it is difficult to see beyond the day when persistent fertility of the soil, under favorable climatic conditions, co-ordinated with great supplies of ores, fuels, and structural materials, will not constitute a decisive and controlling advantage.

Provincialism giving place to cosmopolitanism. The early history of human dispersal was marked by pronounced provincialism. The early peoples were much isolated by distance and by natural barriers, and they often interposed artificial barriers against free inter-communication, and hence against the development of a common cosmopolitan type. So long as hunting and fishing were the dominant pursuits, a wider and wider dispersion into small tribes was a necessary tendency, which was abetted by conflict of interests. That such artificial sources of provincialism were more effective than natural ones seems to be implied by the fact that while physiological differences sufficiently marked to readily characterize varieties were numbered by hundreds, dialects sufficiently different to prevent free intercourse were numbered by thousands. Provincial sentiment to-day manifests itself more conspicuously in language than in most other ways. The tendency to provincialism, however, has never gone so far as to divide the race into distinct species.

When efficient water-transportation was developed and the control of the sea attained, a period of cosmopolitan tendency was inaugurated. This has been greatly accelerated in the last few

decades, supplemented by swift land-transportation and electric communication, and is rapidly involving the whole race in a cosmopolitan movement. Almost the whole world is already in daily communication, and almost all the races are more or less habitually intermingling by travel and trade. That this is to become more and more habitual until the whole race shall be in constant intercommunication, is not to be questioned. There will then have been inaugurated the most marked period of cosmopolitanism, in all senses of the term, which the world has ever witnessed. What all this will ultimately mean for the race we do not venture to predict.

Man as a geological agency. The earlier geologists were inclined to regard man's agency in geological progress as rather trivial, perhaps because physiographic geology, in which his influence is chiefly felt, was then less cultivated than other phases with which he has little to do. The fact probably is that no previous agent, in an equal period of time, has so greatly influenced the life of the land, or the rate of land-degradation, as man has since the present agricultural epoch was well established. That this influence will be increased during coming centuries seems clear. The flora is rapidly passing from that which had been evolved by natural agencies through the ages, to that which man selects for cultivation or preservation, together with that which has taken advantage of the special conditions he furnishes. With the further progress of this movement, the native floras seem destined to an early extinction. The same may be said of the native faunas. The favored animals, under man's care, flourish beyond precedent, while the others, so far as they are within his reach, are suffering rapid declines that look toward extinction. The life of the sea is less profoundly affected than that of the land, but even that does not escape modification. The most pronounced exceptions to man's dominance, and those that bid fair to contest his supremacy longest, are found in organisms too minute to be easily controlled by him, and in organisms that, quite against his wish, flourish on the conditions he furnishes. But even the accelerated evolution of these organisms is a part of the profound biological revolution which attends man's dominance.

Man's control has not thus far been characterized by much recognition of the complicated interrelations of organisms and of the consequences of disturbing the balance in the organic kingdom, and he is reaping, and is certain to reap more abundantly, the unfortunate fruits of ignorant and careless action. For the greater part, man has been guided by immediate considerations, and even these not always controlled by much intelligence. Thus great wantonness has attended his destruction of both plant and animal life. But a more intelligent as well as a more sympathetic attitude is developing, and will doubtless soon become dominant. A new era in control and in evolutionary selection is dawning. New varieties and races are being produced that not only depart widely from the parent stock, but diverge in lines chosen to meet given conditions, or to produce desired products. How far this may yet go it is impossible now to predict.

Prognostic Geology. The long perspective of the past should afford at least some suggestions of the future, but it must be confessed that the most important conjectures as to the future are dependent on interpretations of the past that are not yet certain. A word has been said relative to a possible return of a glacial epoch, but no sure prediction can be made. Question has been raised as to whether the deformations of recent times are over, but the answer remains uncertain. The duration of the earth as a habitable globe has been a common theme of prognosis. A final refrigeration as the result of the secular cooling of a once molten globe has been the usual forecast, and the final doom of the race has been a favorite theme for pseudo-scientific romances. But this all hangs on the doctrine of a former molten earth, if not on the doctrine of its origin from a gaseous nebula. Under the alternative conception of a slow-grown earth conserving its energies, conjoined with a more generous conception of the energies resident in the sun and the stellar system, no narrow limit need be assigned to the habitability of the earth. A Psychozoic era, as long as the Cenozoic or the Paleozoic, or an eon as long as the cosmic and the biotic ones, may quite as well be predicted as anything less. The forecast is at best speculative, but an optimistic outlook seems more likely to prove true than a pessimistic one. An immeasurably

higher evolution than that now reached, with attainments beyond present comprehension, is a reasonable hope.

The forecast of an eon of intellectual and spiritual development comparable in magnitude to the prolonged physical and biotic evolutions, lends to the total view of earth-history great moral satisfaction, and the thought that individual contributions to the higher welfare of the race may realize their fullest fruits by continued influence through scarcely limited ages, gives value to life and inspiration to personal endeavor.

APPENDIX

REFERENCE TABLE OF THE PRINCIPAL GROUPS OF PLANTS.

THALLOPHYTES (Thallus plants)	{	Algae and algaoid forms	{	Diatomaceae, diatoms.	{	True algae						
				Coccospheres			Pelagic algæ.					
				Rhabdospheres								
				Cyanophyceae, blue-green algæ.								
				Chlorophyceae, green algæ, including stoneworts.								
				Rhodophyceae, red algæ.								
				Phaeophyceae, brown algæ.								
							{	Fungi and fungoid forms	{	Myxomycetes, "animal fungi," slime-molds.	{	
										Schizomycetes, "fission-fungi," bacteria.		
										Phycomycetes, algæ-fungi, water-molds.		
Ascomycetes, ascus-fungi, mildews.												
Basidiomycetes, basidium-fungi, smuts, rusts, mushrooms.												
Symbiont algæ and fungi.												
BRYOPHYTES (Moss plants)	{	Lichens	{			{						
		Hepaticæ, liverworts.										
		Musci, mosses.										
PTERIDOPHYTES (Fern plants)	{	Lycopodiales.	{		Lepidodendra, sigillarias, club-mosses.	{						
		Sphenophyllales.										
		Equisetales										
		Filicales		Calamites.								
				Equisetæ, scouring-rushes, horse-tails.								
				Filices, true ferns.								
SPERMATOPHYTES (Seed plants)	{	Gymnospermæ (naked seed)	{	Cycadofilicales.	{							
				Bennettitales.								
				Cycadales.								
				Cordaitales.								
				Ginkgoales.								
		Coniferales.										
		Gnetales.										
		Angiospermæ (covered seed) (Flowering plants)		Dicotyledoneæ. most common forest trees (except conifers), most shrubs and most netted-veined leaved herbs.								
				Monocotyledoneæ, cereals, grasses, etc.								

REFERENCE TABLE OF THE PRINCIPAL GROUPS OF ANIMALS¹

PROTOZOA (the simplest animals)	{	Rhizopoda	{ Foraminifera.
		Flagellata	{ Radiolaria.
		Infusoria	{ Unknown in fossil state.
		Gregarina	{
COELENTERATA (Sponges, corals, jellyfishes)	Porifera	Spongiæ	{ Calcareous sponges.
	Cnidaria		{ Silicious sponges.
	Pelmatozoa	{ Anthozoa, coral polyps.	
		{ Hydrozoa, hydroids and medusæ.	
		{ Cystoidea, cystids.	
ECHINODERMATA (Crinoids, starfishes, sea-urchins)	Asterozoa	{ Crinoidea, stone lilies.	
		{ Blastoidea, blastids.	
		{ Ophiuroidea, brittle-stars.	
		{ Asteroidea, starfishes.	
		{ Echinoidea, sea-urchins.	
	Echinozoa	{ Holothuroidea, sea-cucumbers.	
		{ Platyhelminthes	
VERMES (Worms)		{ Rotifera	{ Rare as fossils.
		{ Nemathelminthes	
		{ Gephyrea	
		{ Annelida, sea-worms.	
MOLLUSCOIDEA (Mollusc-like forms)		{ Bryozoa, sea-mosses.	
		{ Brachiopoda, lamp-shells.	
		{ Pelecypoda, lamellibranchs, bivalves.	
		{ Scaphopoda, tusk-shells.	
		{ Amphineura, chiton.	
		{ Gastropoda, univalves, snails, etc.	
		{ Cephalopoda, nautilus, cuttlefish.	
		{ Crustacea.	
		{ Trilobita, trilobites.	
		{ Gigantostraca, horseshoe crabs.	
		{ Entomostraca, ostracoids, barnacles.	
		{ Malacostraca, lobsters, crabs.	
		{ Myriapoda, centipedes.	
		{ Arachnoidea, spiders, scorpions.	
		{ Insecta, insects.	
		{ Cyclostomata, lampreys.	
		{ Selachii, sharks.	
		{ Holocephali, spook-fishes.	
		{ Dipnoi, lung-fishes.	
		{ Teleostomi, ganoids and teleosts, (common fishes).	
		{ Amphibia, amphibians, batrachians.	
		{ Reptilia, reptiles.	
		{ Aves, birds.	
		{ Prototheria, monotremes.	
		{ Metatheria, marsupials.	
		{ Eutheria, placentals.	
ARTHROPODA (The articulates)	Branchiata		
	Tracheata		
VERTEBRATA			

¹ After Zittel in the main.

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